Efficient Spectrum-Handoff Schemes For Cognitive Radio Networks

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As the candidate's supervisor, I have approved this dissertation for submission

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Declaration

I hereby declare that: (1) The above thesis is my own unaided work, both in conception and execution, and that apart from the normal guidance of my supervisor, I have received no assistance apart from that stated below; (2) except as stated below, neither the substance or any part of the thesis, has been submitted in the past, or is being or is to be submitted for a degree in the University or any other University.

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Periola Ayodele Abiola   December 05, 2016

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Dedication

To the Loving Memory of Bayo Periola

who first taught me "*Introductory*" further mathematics and gave me my first copy of

Pure Mathematics by J.K. BackHouse and S.P.T. Houldsworth

Acknowledgements

All thanks to the Almighty God for the gift of life and manifold blessings that are too numerous to count. I acknowledge the Almighty God for his help and grace. All praises to God. My thanks also go to my parents and siblings for their fortitude, spiritual support and financial support. Without them, it could have been extremely challenging for me to complete this thesis.

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List of Abbreviations

ADCS – Attitude Determination and Control Subsystem

ALMA – Atacama Large Millimetre/ Sub Millimetre Array

ANN - Artificial Neural Network

ANTS – Autonomous Nano Technology Swarm Framework

AS – Astronomical Source

BS- Base Station

CCE – Computing Infrastructure Entity

CCM- Central Computational Module

CC- FNN – Cascade Multilayer Feed Forward Neural Network

CE – Cognitive Engine

CEON – Cognitive Earth Observation Network

CPP – Cognitive Priority Protocol

CR – Cognitive Radio

CRP – Cognitive Radio Paradigm

CSIT – Channel State and Idle Time

CSS – Communication Subsystem

DDS – Data Downlink Stage

DML – Decision Making Layer

DSA – Dynamic Spectrum Allocation

DTT – Data Transmit Time

DUS – Data Uplink Stage

ECV – Earth Climate Variable

CEOs – Earth Observations

EOPS – Earth Observation and Payload Subsystem

ESN – Echo State Network

FIEOS – Future Intelligent Earth Observation System

Fracsat - Fractionated Satellite System

FSA – Fixed Spectrum Allocation

F6MDA – F6 Model Driven Architecture

GAI – Generative Artificial Intelligence

GBT - Ground Based Telescope

GEO – Geostationary Orbit

GSM – Global System for Mobile Communications

HMM – Hidden Markov Model

HPC – High Performance Computing infrastructure

HSN – Heterogeneous Spacecraft Network

HWN – Heterogeneous Wireless Network

ISL – Inter-satellite Link

ISH – Input-Source Heterogeneity

KAT – Karoo Array Telescope

LA – Learning Algorithm

LCP – LA Classification Pause

LDS – Learning Diversity Selection

LEO – Low Earth Orbit

LTE – Long Term Evolution

LTE-A – Long-Term Evolution Advanced

MES – Multimode Earth Station

MGL – Measurement Gap Length

MGS –Mobile Ground Station

MGRP – Measurement Gap Repetition Period

MIMO – Multiple Input Multiple Output

ML-FNN – Multilayer Feed-Forward Neural Network

MM - Master Module

MSE – Mean Square Error

MUD – Multiuser Detector

NSC – Neural Similarity Condition

OCSS – On-board Computing Subsystem

OFDM –Orthogonal Frequency Division Multiplexing

OFL – Optic Fibre Link

PE – Power Efficiency

PNSats – Pico and Nano Satellites

POS – Parameter Observation Stage.

PS – Power Subsystem

PU – Primary User

QoS – Quality of Service

RAOs – Radio Astronomy Observations

RAT – Radio Access Technology

RQZ – Radio Quiet Zone

RRC – Radio Resource Control

SAI – Satellite Astronomy Interface

SDMA- Space Division Multiple Access

SDR – Software Defined Radio

SH – Spectrum Hole

SINR – Signal to Interference Plus Noise Ratio

SOM-NN – Self Organizing Map Neural Network

SRAO – Space Radio Astronomy Observation

SSD – Space Segment Delay

SU- Secondary User

SVB – Satellite Visibility Database

SVM – Support Vector Machine

SW – Spectral Window

TRAO – Terrestrial Radio Astronomy Observation

TRQZ – Terrestrial Radio Quiet Zone

TWNs – Terrestrial Wireless Networks

UMTS – Universal Mobile Telecommunication System

VIF – Visibility Interface

WCM- Wireless Communications Module

WSM – Weather Sensing Module

Abstract

Radio spectrum access is important for terrestrial wireless networks, commercial earth observations and terrestrial radio astronomy observations. The services offered by terrestrial wireless networks, commercial earth observations and terrestrial radio astronomy observations have evolved due to technological advances. They are expected to meet increasing users' demands which will require more spectrum. The increasing demand for high throughput by users necessitates allocating additional spectrum to terrestrial wireless networks. Terrestrial radio astronomy observations s require additional bandwidth to observe more spectral windows. Commercial earth observation requires more spectrum for enhanced transmission of earth observation data. The evolution of terrestrial wireless networks, commercial earth observations and terrestrial radio astronomy observations leads to the emergence of new interference scenarios. For instance, terrestrial wireless networks pose interference risks to mobile ground stations; while inter-satellite links can interfere with terrestrial radio astronomy observations. Terrestrial wireless networks, commercial earth observations and terrestrial radio astronomy observations also require mechanisms that will enhance the performance of their users.

This thesis proposes a framework that prevents interference between terrestrial wireless networks, commercial earth observations and terrestrial radio astronomy observations when they co-exist; and enhance the performance of their users. The framework uses the cognitive radio; because it is capable of multi-context operation.

In the thesis, two interference avoidance mechanisms are presented. The first mechanism prevents interference between terrestrial radio astronomy observations and inter-satellite links. The second mechanism prevent interference between terrestrial wireless networks and the commercial earth observation ground segment. The first interference reductionmechanism determines the inter-satellite link transmission duration. Analysis shows that interference-free inter-satellite links transmission is achievable during terrestrial radio astronomy observation switching for up to 50.7 seconds. The second mechanism enables the mobile ground station, with a trained neural network, to predict the terrestrial wireless network channel idle state. The prediction of the TWN channel idle state prevents interference between the terrestrial wireless network and the mobile ground station. Simulation shows that incorporating prediction in the mobile ground station enhances uplink throughput by 40.6% and reduces latency by 18.6%.

In addition, the thesis also presents mechanisms to enhance the performance of the users in terrestrial wireless network, commercial earth observations and terrestrial radio astronomy observations. The thesis presents mechanisms that enhance user performance in homogeneous and heterogeneous terrestrial wireless networks. Mechanisms that enhance the performance of LTE-Advanced users with learning diversity are also presented. Furthermore, a future commercial earth observation network model that increases the accessible earth climatic data is presented. The performance of terrestrial radio astronomy observation users

is enhanced by presenting mechanisms that improve angular resolution, power efficiency and reduce infrastructure costs.

The thesis develops a dual mode mechanism that uses learning and enhances user performance in homogeneous and heterogeneous terrestrial wireless networks. It also proposes the incorporation of learning-diversity selection and learning-classification pause to enhance performance of users (with learning diversity). The mechanisms proposed to enhance user performance in terrestrial wireless network reduce the overhead associated with learning-algorithm development in intelligent terrestrial wireless network users.

Terrestrial radio astronomy observation user performance is enhanced in a scenario comprising multimode earth stations, ground based telescopes and high performance computing infrastructure. The multimode earth stations and ground based telescopes co-exist with cognitive terrestrial wireless networks. Interactions between terrestrial wireless networks and the high performance computing infrastructure enables the terrestrial wireless network to make opportunistic use of the underutilised high performance computing infrastructure. The terrestrial wireless network uses the underutilised high performance computing infrastructure to train its learning algorithms thereby enhancing terrestrial radio astronomy observation power efficiency and terrestrial wireless network autonomy. The use of multimode earth stations alongside ground based telescopes enhance angular resolution and reduce terrestrial radio astronomy observation infrastructure cost.

In addition, user performance in commercial earth observation networks is enhanced in the proposed cognitive earth observation network. The cognitive earth observation network incorporates fractionated small satellites and mobile ground stations in the space and ground segment, respectively. The space segment uses a bio-inspired mechanism for fractionated satellite module sharing thereby making the cognitive earth observation network robust to module failures. The cognitive earth observation network also enables users to access more earth climatic data at higher throughput and low latency.

Furthermore, the thesis formulates performance models for mechanisms that improve user performance in terrestrial wireless networks, commercial earth observations and terrestrial radio astronomy observations. The performance benefits of these mechanisms are investigated via numerical simulation. The performance of the dual mode mechanism proposed for terrestrial wireless network users without learning diversity is compared with the existing channel state and the idle time. Analysis shows that the dual mode mechanism enhances throughput by 31% and 36% in the homogeneous and heterogeneous mode, respectively. Numerical simulations also show that using multimode earth station enhances terrestrial radio astronomy observation angular resolution by 59.2%. In addition, high performance computing infrastructure-cognitive terrestrial wireless network sharing enhances high performance computing infrastructure power efficiency by 8.31%. Furthermore, the use of cognitive radio for fractionated satellite-module soft sharing increases the commercial earth observation network's accessible data by 20%.

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List of Parameters

L	Set of radio access technologies (RATs).
L_U	The U^{th} RAT
$\beta_L^i(t)$	Spectrum usage parameter matrix comprising i parameters for L at instant t.
$C(\beta_{L_U}^1(t)$	Cardinality of $\beta_{L_U}^i(t)$
$p_{L_1}(t_z)$	CR probability distributions formed from β_{L_1}at instant t_z ; $t_z \epsilon\ t$.
$\kappa_L^{i'}(t)$	CR configuration parameters comprising i' parameters in L
$W_L(t)$	Set of CR's artificial neural network (ANN) weight matrices for L
i_L	CR Similarity Indicator in L
$I_{L_f}^{L_e} \epsilon \{0,1\}$	Parameter similarity indicator between RATs L_e and L_f ; $(L_e, L_f \epsilon L)$
z_L	CR training parameter acquisition indicator in L.
$F(W_L(t))$	Status of $W_L(t)$.
L_{CR}	CR Location
C_{ind}	Index of channel in L.
C_{sel}	Selected channel in L.
C_τ^{PU}	Primary user duty cycle in channels in L
C_{st}	State of channels in L
T_{con}	Allowable connection duration of the CR-SU on a channel in L
T_{act}	Actual connection duration of the CR-SU on a channel in L
δ	Similarity threshold for determining similarity between CR training parameters
S_M	Channel Slot Duration.
S_L	MGL
C	Set of TWN Channels.
$B_{b'}$	Bandwidth of channel $c_{b'}$; $c_{b'} \epsilon\ C$ in MHz
$h_{b'}^t$	CR's Transmit gain on $c_{b'}$
$P_{b'}^t$	CR's Transmit power on $c_{b'}$
$h_{b'}^{in}$	Transmit gain of interfering neighbour on $c_{b'}$
$P_{b'}^{in}$	Transmit power of interfering neighbour on $c_{b'}{}'$
σ^2	Additive white Gaussian noise (AWGN)
ΔS_I	Increase in MGL due to the acquisition of training experience from more neighbouring CRs.
τ_1	Transmit duration per channel in a single mode CR that uses proposed mechanism.
γ	MGL reduction in single mode CR using proposed mechanism (homogeneous mode) in L.
τ_2	Transmit duration per channel in dual mode CR with proposed mechanism (homogeneous mode).
ζ	Delay arising due to non-ideal concurrency in dual mode CR.
τ_3	Transmit duration per channel in dual mode CR with proposed mechanism (heterogeneous mode).
$\ddot{\alpha}$	Fraction of MGL spent by CR to verify predicted outputs in proposed mechanism (heterogeneous mode)
$\ddot{\upsilon}$	Missing parameter acquisition duration from CR neighbouring database in proposed mechanism.
$P_{md}^{b'}$	CR misdetection probability when verifying ANN predicted results for b'
PLR_1	Packet Loss Rate of CR using proposed mechanism (heterogeneous mode).
$P\left(\beta_L^i(t)\right)$	Probability that the CR correctly predicts $\beta_L^i(t)$ for L.
$\mathfrak{L}(t)$	Set of learning algorithms (LAs) in CR that incorporates learning diversity at instant t.
$Q(t)$	Set of observed CR QoS for LA in CR that incorporates learning diversity at instant t.
P	Initial battery power for CR that incorporates learning diversity
r	Set of cognition engines (CEs) in the CR that incorporates learning diversity.
r_u	The CR's u^{th} CE.
$P_{ta}(\mathfrak{L}(t))$	CR battery power expended in training LAs in the CR that incorporates learning diversity at instant, t.
$P_{cl}(\mathfrak{L}(t))$	CR battery power expended in classifying LAs in CR that incorporates learning diversity at instant, t.
$P_{ta}\left(\mathfrak{L}_q(t_p)\right)$	CR battery power expended in training LA $\mathfrak{L}_q$at instant t_p ; $\mathfrak{L}_q(t_p) \epsilon\ \mathfrak{L}(t)$
$P_{cl}\left(\mathfrak{L}_q(t_p)\right)$	CR battery power expended in classifying $\mathfrak{L}_q$at instant t_p.
$P_{tr}(\mathfrak{L}_q(t_p))$	CR data transmit power when CR uses a LAs at instant t_p.
$I_q(t)$	Best LA indicator signifying that an LA is the best for CR spectrum prediction at instant t.
$P'_{tr}(\mathfrak{L}_q(t_p))$	Data transmit power when CR uses LDS at instant $t_{p'}$.
T_q^{ta}	LA training duration for the LA q in the CR that incorporates learning diversity.
ϑ	Transmit duration of CR that incorporates learning diversity with existing mechanism.
ϑ'	Transmit duration of CR that incorporates learning diversity with proposed LDS.
$P_{b'}^1$	Data transmit power on $c_{b'}$ for CR with learning diversity but without LDS.
$P_{b'}^2$	Data transmit power on $c_{b'}$ for CR with learning diversity with LDS.
Th_1	Throughput of CR with learning diversity but without LDS.
Th_2	Throughput of CR with learning diversity with LDS.
D_1	Amount of data transmitted when CR does not use LDS.

D_2	Amount of data transmitted when CR uses LDS.
r	Set of cognition engines (CEs) in CR that use LCP.
N_{LA}^{u}	Number of LAs in r_u ; $r_u \epsilon\, r$.
θ_u^v	Number of connections between r_u and r_v ; $r_v \epsilon\, r$
ψ_1	Number of CEs connected to r_1
ρ_1	Number of layers between r_1 and CR's resources
Ω	CR- Price of Maintaining Consciousness in CR that uses existing mechanism.
Ł	Reduction in CR transmit power.
N_p^u	Number of CR's paused CEs in r_u.
N_T	Total number of CR's CE layers
µ	Pause-transfer efficiency.
P	Initial CR data transmit power.
P'	Data transmit power of CR that incorporates learning diversity and uses LCP.
Ω''	CR- PMC of CR that engages in spectrum sharing and uses existing mechanism i.e. without LCP.
P''	Transmit power of CR with learning diversity that engages in spectrum sharing and incorporates LCP.
$P_{b'}^{A_1}$	Data transmit power of CR that does not engage in spectrum sharing and does not incorporate LCP.
$P_{b'}^{A_2}$	Data transmit power of CR that does not engage in spectrum sharing and uses LCP
$P_{b'}^{A_3}$	Data transmit power of CR that does engages in spectrum sharing and uses LCP
Th_{A_1}	Throughput of CR that does not engage in spectrum sharing and does not use LCP
Th_{A_2}	Data transmit throughput of CR that does not engage in spectrum sharing and uses LCP
Th_{A_3}	Data transmit throughput of CR that engages in spectrum sharing and uses LCP
F	Set of Radio Frequencies for ISL transmission and GBT observation.
S	Set of ISLs used by LEO satellites.
Φ	Set of GBTs.
s_1^f	ISL l_1 using f.
ϕ_a^f	GBT used for terrestrial radio astronomy observation (TRAO) over sky region a using f.
X	Entity X, X could be either S or ϕ
I_X^f	Spectrum usage indicator of X
$\phi_1^{f_1}$	GBT $\phi_1$using frequency f_1 for TRAOs, $f_1 \epsilon f$.
$I(\Upsilon)$	Indicator signifying that GBT can or cannot meet ϒ
$I(L)$	TWN indicator indicating absence or presence of L in GBT vicinity
τ	Set of duty cycle of high performance computing infrastructure (HPC) at instant t.
τ_{thr}	Threshold HPC duty cycle.
$ð_1$	Angular resolution when only converted GBTs are used for TRAOs in absence of TWNs.
$ð_2$	Angular resolution when GBTs and MESs are used for TRAOs in absence of TWNs.
$ð_3$	Angular resolution when MESs and GBTs are used for TRAOs; there is TWN interference.
$ð_4$	Angular resolution when MESs and GBTs are used in presence of TWNs with interference protection.
Sc	Probability of having sufficient HPC resources
Sa	Probability of functional computing module in HPC.
Sp	Probability of using HPC to train cognitive TWN algorithms.
α	Set of fractionated satellites (fracsats) used in the commercial earth observation network.
ⱪ	Set of fractionated satellite module
$\theta_ⱪ$	Orbital inclination
$S_{h_{ⱪ_1}}^{\alpha_r,\theta_{ⱪ_1}}$	α_r's first module.
$I\left(S_{h_{ⱪ_1}}^{\alpha_r,\theta_{ⱪ_1}}\right)$	Functional status of $S_{h_{ⱪ_1}}^{\alpha_r,\theta_{ⱪ_1}}$.
$I_t^{b'}$	Channel usage indicator for $c_{b'}$ at instant, t. $c_{b'} \,\epsilon\, C$
x	Index used to refer to either input ip, hidden ih or output layers ho of the MGS's ML-FNN.
N_x	Number of layer neurons in x.
$f_x(.)$	Transfer function in x
w_x	Weights of x.
Th_{nb}	MGS uplink throughput when channels are not bonded.
Th_b	MGS uplink throughput when channels are bonded.
$B_{c_{b'}}$	Bandwidth of C_s in Hz.
D_{α_r}	Data captured by α_r's WSM ; $\alpha_r \epsilon\, \alpha$
L_{α_r}	Total ECV accessed from ECV in space segment.
I_{α_r}	WSM functional indicator.

List of Outputs from Thesis

The research described in this thesis has generated ideas that have resulted in the following research outputs:

Journal Papers

J1: A.A. Periola and O.E.Falowo, '***Intelligent Cognitive Radio Models for Enhancing Future Radio Astronomy Observations***' Advances in Astronomy, (Published).

J2: A.A.Periola and O.E. Falowo, '***Cognitive Radio Spectrum Prediction Using a Robust Neural Network***' IET Communications, Submitted July 2016.

J3: A.A.Periola and O.E. Falowo , '***Cognitive Communications for Commercial Networked Earth-Observing Fractionated Small Satellites***', Wireless Personal Communications, Manuscript Number: WIRE-D-15-02030. Submitted November 2015.

Conference Papers

C1: A.A.Periola and O.E.Falowo, '***A Robust Conscious Model for Enhancing Cognitive Radio Quality of Service***', IEEE Personal Indoor Radio and Mobile Communications, Valencia, Spain, Sept 2016, pp 2067-2072

C2: A.A.Periola and O.E. Falowo, '***Learning Diversity Selective Algorithm for Enhancing Cognitive Radio Quality of Service***' South African Conference on Telecommunications and Network Applications, George South Africa, South Africa, 4-9 Sept 2016, pp 38-44

C3: A.A.Periola and O.E. Falowo, '***Cognitive Models for Improving Radio Astronomy and Enabling Autonomous Wireless Networks***' South African Conference on Telecommunications and Network Applications, Hermanus, South Africa, 6-9 Sept 2015, pp 361-366.

C4: A.A.Periola and O.E. Falowo, '***Interference protection of radio astronomy services using cognitive radio spectrum sharing models***' European Conference on Networks and Communications, Paris France, June 2015, pp 86-90.

C5: A.A.Periola and O.E.Falowo, '***Immuno-neural network for spectrum prediction***' IEEE International Conference on Advanced Networks and Telecommunications Systems, New Delhi, India, Dec 2014, pp 1-6.

Chapter 1

1.1 Introduction

Spectrum access is important for terrestrial-wireless networks, commercial-earth observations and terrestrial radio-astronomy observations. The services offered by terrestrial-wireless networks, commercial-earth observations and terrestrial radio-astronomy observations require more spectrum, because of technological advances and new user expectations. Increasing terrestrial wireless network mobile users require high bandwidth access for proliferating high throughput applications, such as online video. Similarly, the proliferation of low-cost small satellites due to electronic miniaturization fuels the growth of commercial earth observation. Commercial earth observation aims to provide users with high throughput access to earth climatic data. They require additional bandwidth to realise their goal of high throughput. In addition, terrestrial radio astronomy observations are also being increasingly considered by more nations. The increasing spectrum demand of terrestrial wireless networks, commercial earth observation and terrestrial radio astronomy observations increases the pressure on spectrum allocation.

This thesis proposes a framework that reduces interference between terrestrial wireless networks, commercial earth observation and terrestrial radio astronomy observations when they co-exist; and improve the performance of their users.

1.2 Radio-Spectrum Access and Utilisation

The radio spectrum is a finite resource required to achieve high throughput data transmission by terrestrial wireless networks, commercial earth observations and terrestrial radio astronomy observations. Terrestrial wireless networks and commercial earth observation require additional spectrum to provide users with increased throughput. In terrestrial radio astronomy observations, additional spectrum is required to enable ground based telescopes receive radio signals from new spectral windows . The increasing spectrum demand of terrestrial wireless networks, commercial earth observation and terrestrial radio astronomy observations puts more pressure on radio-spectrum allocation. The spectrum-access objectives of the terrestrial wireless networks, commercial earth observations and terrestrial radio astronomy observations should be satisfied with reduced interference. A new spectrum-allocation framework that jointly satisfies the spectrum access demands for terrestrial wireless networks and other technologies like commercial earth observations and terrestrial radio astronomy observations is required [1-3].

The design of a new spectrum-allocation framework for terrestrial wireless networks, commercial earth observations and terrestrial radio astronomy observations is also necessitated by new user expectations. Terrestrial wireless networks have a high adoption rate; and they require additional spectrum to support more users at improved quality of service [2,4]. Earth observations now aim to derive insights from ubiquitous earth-climatic variable data. This leads to the emergence of commercial earth observation.

The goal of ubiquitously accessing earth climatic variable data poses a challenge of spectrum conflict between commercial earth observations and terrestrial wireless networks. Terrestrial wireless networks comprise base stations and mobile subscribers; while commercial earth observation consist of mobile ground stations as terrestrial entities. Collocated mobile subscribers and mobile ground stations pose interference risks to each other, when they seek to maximize uplink throughput. Hence, new spectrum-allocation models that consider the spectrum-access objectives of commercial earth observation and terrestrial wireless networks are required.

The maturation of low cost small satellite technology has led to their use in earth observation [5] and communications [6-11]. Small satellite constellations can provide global coverage and forward data between satellites via inter-satellite links. Intersatellite links enable data to be forwarded between locations via the space segment. However, the use of intersatellite links poses interference risks to terrestrial radio astronomy observations [12]. Terrestrial radio astronomy observations study the universe and analyse astronomy-source radio signals received by ground based telescopes. The radio signals emitted by astronomy sources traverse space; and they are corrupted by intersatellite link signals prior to reception at ground based telescopes. The interference challenge arises between terrestrial radio astronomy observations and satellites as seen in [12] and terrestrial radio astronomy observations and terrestrial wireless networks as seen in [13].

The increasing interest in terrestrial radio astronomy observations has been noted in [14-15]; and it gives rise to two challenges. The first challenge is enhancing the angular resolution when terrestrial radio astronomy observations are conducted using converted ground based telescopes. The second is improving high-performance computing infrastructure utilisation.

This thesis uses the cognitive-radio paradigm to address these challenges. The cognitive radio paradigm is used; because it supports robust mechanisms and dynamic spectrum access. Dynamic spectrum access can enable terrestrial wireless networks, commercial earth observation and terrestrial radio astronomy observation to make use of each other's unused spectrum, with reduced interference. In addition, dynamic spectrum access enhance spectrum utilisation. Furthermore, the cognitive radio is reconfigurable. The cognitive radio is also suitable for enhancing user quality of service in terrestrial wireless networks, commercial earth observations and terrestrial radio astronomy observations.

1.3 Spectrum Utilisation and the Cognitive-Radio Paradigm

This section discusses the spectrum utilisation observed from measurement campaigns. It identifies the role of the cognitive radio paradigm; and it discusses the spectrum-usage measurement results. The discussion on the incorporation of cognitive radio paradigm to enhance spectrum utilisation focuses more on terrestrial wireless networks instead of commercial earth observations and terrestrial radio astronomy observation. The focus is on terrestrial wireless network because they make more use of the radio spectrum [2].

Measurements [16] show that terrestrial wireless networks have low spectrum usage at different locations. This implies that terrestrial wireless networks do not use their allocated spectrum all the time. Martian *et al.* [17] examined the mean spectral occupancy for the (25-3400) MHz band. The mean spectrum utilisation is evaluated to be 21% and 14% in urban and rural areas, respectively. The underutilisation in [16-17] arises because fixed spectrum allocation does not incorporate spectrum sharing, as does dynamic spectrum access . The dynamic spectrum access mechanisms should improve spectrum utilisation and reduce interference between the existing subscribers [18-20]. In this thesis, dynamic spectrum access mechanisms should reduce interference between terrestrial wireless networks, commercial earth observations and terrestrial radio astronomy observations when they co-exist.

The cognitive radio paradigm incorporates dynamic spectrum access; and it considers two types of users: primary users and secondary users. Primary users have a higher spectrum-access priority than secondary users. The cognitive priority protocol governs primary user- secondary user spectrum sharing; and it stipulates that secondary users should not interfere with primary users. Secondary users sense the radio spectrum and can detect the presence of primary users. They transmit data in vacant spectrum holes i.e. channels. The role of the cognitive priority protocol in governing spectrum access is shown in Figure 1-1.

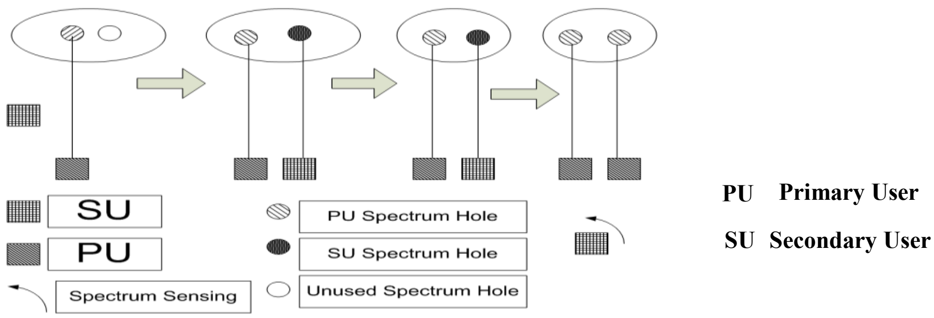

Figure 1-1: Spectrum handoff in cognitive networks.

Figure 1-1 shows the spectrum-handoff initiation and execution between primary users and secondary users with two spectrum holes. Initially, the primary user is connected to one spectrum hole. However, a secondary user performing spectrum-sensing desires spectrum access. The secondary user detects and uses the vacant spectrum hole for transmission. A new primary user enters; while the secondary user occupies the spectrum hole. The secondary user detects primary user entry, exits the occupied spectrum hole and initiates spectrum sensing to find another vacant spectrum hole. Secondary users can be designed by using cognitive radio technology. The cognitive radio is capable of awareness acquisition, inferential reasoning, decision-making and execution [19-20]. These functions constitute the cognitive radio cycle, as shown in Figure 1-2. In Figure 1-2, the cognitive radio senses the environment, reasons using sensed data, makes reconfiguration decision and execute the decision.

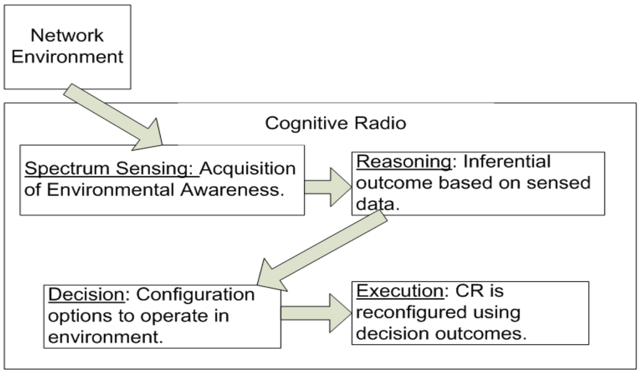

Figure 1-2: Cognitive radio cycle.

The cognitive radio uses intelligent mechanisms to determine transmission parameters that enhance user quality of service [18, 21] and uphold the cognitive priority protocol [18]. Intelligent mechanisms with learning ability have been used for spectrum-sensing [22] and channel prediction [23] in cognitive radios. Xing *et al.* [23] examine techniques, such as hidden Markov model, support vector machines and artificial neural networks . Artificial neural networks are preferred to hidden Markov models; because the artificial neural network is easily scalable [24-25].

Support vector machines are more suitable than artificial neural networks for classification [25-26] given large training samples, multiple inputs and outputs [26-28]. Artificial neural networks have been widely considered for cognitive radio spectrum prediction [29-30]. However, artificial neural networks have a poor generalisation capability. Hence, training data re-acquisition is required. This thesis uses the artificial neural network for cognitive radio learning because of its low cost top down modelling approach.

1.4 Problem Statement

This thesis addresses the problem of interference between terrestrial wireless networks, commercial earth observation and terrestrial radio astronomy observations and enhancing the quality of service experienced by their users. The services offered by terrestrial wireless networks, commercial earth observation and terrestrial radio astronomy observations are evolving due to technological advances and new user expectations. Terrestrial wireless networks and commercial earth observation require additional bandwidth to provide users with high throughput and low latency data access. Terrestrial radio astronomy observation also require access to new spectral windows to observe astronomy sources. The allocation of more spectrum to terrestrial wireless networks, commercial earth observation and terrestrial radio astronomy observations poses interference challenges when they co-exist. In addition, the additional bandwidth allocation should enhance the user performance in terrestrial wireless networks, commercial earth observation and terrestrial radio astronomy observations. This thesis presents mechanisms that reduce interference and enhance user performance.

1.5 Research Questions and Objectives

This section presents the research questions and the objectives.

1.5.1 Research Questions

The research questions addressed in this thesis are:

1) What improvement in terrestrial wireless network subscriber’s quality of service can be obtained by using enhanced bio-inspired algorithms compared with the existing artificial neural network based mechanisms?
2) How does the incorporation of robust bio-inspired algorithms in cognitive radios improve their quality of service when they have multi-homing capabilities as secondary users in heterogeneous wireless networks?
3) To what degree does the incorporation of cognitive radios and bio-inspired mechanisms enhance the quality of service of future commercial earth observation network models when CEOxisting with terrestrial wireless networks?
4) To what degree does cognitive radio incorporation enhance terrestrial radio astronomy observation angular resolution and improve high performance computing infrastructure utilisation when CEOxisting with terrestrial wireless networks?

1.5.2 Research Objectives

The objectives of this thesis are to:

1) Review the existing literature; and it discusses how advances in technology provide a basis for the research. The review also recognises the existing techniques used for comparison purposes to determine the performance improvement of the proposed algorithms.
2) Model and develop new mechanisms with improved spectrum utilisation and interference reduction are developed for users in terrestrial wireless networks, commercial earth observation and terrestrial radio astronomy observations.
3) Formulate mathematical models that are used to investigate the performance metrics of terrestrial wireless networks, commercial earth observation and terrestrial radio astronomy observations.
4) Evaluate the performance of developed algorithms via numerical simulation. The performance of the algorithms proposed for proposed are compared with the techniques used in the existing algorithms**.**

1.6 Scope and Assumptions

The research described in this thesis considers spectrum allocation for terrestrial wireless networks, commercial earth observation and terrestrial radio astronomy observations. It does not consider the analytical results of meteorological and astronomical data; but it focuses on their spectrum-access objectives. Some of the proposed mechanisms require access to their data. Efforts have been made to obtain data, which were unavailable in some cases. The thesis focuses on the design of intelligent mechanisms for the commercial earth observation network service; and it assumes a functional-link budget.

1.7 Research Contributions

This thesis makes the following contributions:

1) Enhancing spectrum utilisation and user quality of service in terrestrial wireless networks: This thesis proposes a dual mode mechanism that improves spectrum utilisation. The proposed mechanism reduces training overhead and enhances user quality of service in homogeneous and heterogeneous terrestrial wireless networks. Simulation results show that the proposed mechanism outperforms the existing mechanism.
2) Enhancing the performance and efficiency of the LTE-Advanced terrestrial wireless network users with learning diversity: The thesis proposes learning-diversity selection and learning-classification pause to enhance the performance of the LTE-Advanced user with learning diversity. Simulations show that learning-diversity selection and learning classification performance improve the cognitive radio quality of service, when compared with the existing scheme.
3) Interference reduction and enhancing user performance in terrestrial radio astronomy observations: This thesis proposes mechanisms that prevents terrestrial radio astronomy observation-intersatellite link interference, improve angular resolution, high performance computing infrastructure utilisation and reduce terrestrial radio astronomy infrastructure costs. The improvement of angular resolution and infrastructure cost reduction is achieved by using reconfigurable multimode earth stations. The high performance computing infrastructure utilisation is improved by using the underutilised high performance computing infrastructure to train the learning algorithms of a cognitive terrestrial wireless network. Performance models for the algorithms are formulated. Numerical simulations are also used to investigate models' performance.
4) Interference reduction and enhancing user performance in commercial earth observation: The thesis presents mechanisms that reduces interference between commercial earth observation and terrestrial wireless network interference; and enhances commercial earth observation user performance. These mechanisms are integrated in the proposed cognitive earth observation network model. the proposed cognitive earth observation network model comprises fractionated small satellites equipped a bio-inspired mechanism that increases the earth climatic variable data accessible to users. The ground segment hosts the mobile ground station. The mobile ground station hosts the spectrum prediction mechanism that improves spectrum utilisation and uplink throughput. The mathematical formulation of the cognitive earth observation network 's, throughput, latency

and amount of accessible space segment data are presented. Simulation shows that the cognitive earth observation network outperforms the existing model.

1.8 Thesis Outline

The outline for the rest of the thesis is as follows:

Chapter 2: This chapter discusses the challenges in terrestrial wireless networks, commercial earth observations and radio astronomy observations that necessitate a joint consideration for spectrum access. The chapter also presents a unified architecture.

Chapter 3: This chapter presents a dual mode mechanism that enhances cognitive radio (user in terrestrial wireless network) quality of service in terrestrial wireless networks. The proposed mechanism operates in homogeneous and heterogeneous modes. In the homogenous mode, the cognitive radio obtains an enhanced quality of service in a single radio access technology environment. The cognitive radio obtains an enhanced quality of service in the heterogeneous wireless network when the proposed mechanism is in the heterogeneous mode. Simulation results show that the proposed mechanism outperforms the existing algorithm. Results on the proposed mechanisms' homogeneous mode have been presented at the IEEE Conference on Advanced Networks and Telecommunication systems. Results on the proposed mechanism's heterogeneous mode has been submitted to IET Communications and is under review.

Chapter 4: The chapter focuses on enhancing cognitive radio quality of service in LTE-Advanced. The cognitive radio incorporates learning algorithm classification pause and learning diversity selection. In learning classificvation pause, the cognitive radio pauses learning algorithm classification when there are insufficient resources to support data transmission and learning-algorithm classification. Learning diversity selection enhances cognitive radio quality of service by reducing cognitive radio resources used in training learning algorithms. It ranks and selectively trains cognitive radio learning algorithms. The cognitive radio first trains the learning algorithm that enables it to achieve the best quality of service. Performance models are formulated for both algorithms and simulation results show that learning classification pause and learning diversity selection outperform the existing scheme. The results on learning classification pause were presented at the IEEE Conference on Personal Indoor and Mobile Radio Communication. The result on learning diversity selection were presented at the South African Telecommunications and Network Applications Conference.

Chapter 5: This chapter uses the cognitive radio to optimise the terrestrial radio astronomy observations conducted by a terrestrial radio astronomy organisation. The optimisation is realised by protecting terrestrial radio astronomy observations from intersatellite link interference, improving high performance computing infrastructure power efficiency and enhancing angular resolution. Numerical simulation is performed to investigate the spectrum usage and intersatellite link transmit opportunity after achieving interference protection. In addition, simulation results show that incorporating the cognitive radio into terrestrial radio astronomy observation enhances high performance computing infrastructure utilisation and angular resolution. Furthermore, the use of the cognitive radio also reduces terrestrial radio astronomy observation costs. The results have been presented at the European Conference on Networks and Communications and at the South African Telecommunications and Network Applications Conference.. The presented results have been accepted for publication in the Journal of Advances in Astronomy.

Chapter 6: The discussion here protects the commercial earth observation ground segment from LTE-Advanced interference. The interference reduction is achieved by spectrum prediction. The incorporation of spectrum prediction also enhances spectrum utilisation and improves commercial earth observation uplink throughput. In addition, the user performance is also enhanced by designing a robust space segment. The space segment uses low cost fractionated small satellites that incorporate ant polydomy motivated mechanisms. Numerical simulation results show that the cognitive earth observation network model outperforms the throughput, latency and amount of accessible data of the existing model. The presented results have been submitted for review to the journal of Wireless Personal Communications.

Chapter 7: This chapter concludes the thesis and outlines some possible directions for future work.

Chapter 2

Background and Literature Review

The radio spectrum is an important resource for users in terrestrial wireless networks (TWNs), commercial earth observation (CEO) and terrestrial radio astronomy observation (TRAO). TWNs and CEOs users require access to the radio spectrum for the purposes of enhanced data transmission. TRAO require spectrum access to observe astronomical source (AS) signals. The discussion in this chapter reviews existing research on the spectrum access objectives of TWNs, CEO and TRAO. Different portions of the radio spectrum are allocated to TWNs, CEOs and TRAOs. The allocated spectrum is used to meet different user objectives. The discussion in this chapter focuses on the spectrum access concerns of TWNs, CEO and TRAO.

The rest of this chapter is divided into seven sections. The first section discusses spectrum demand, utilisation and allocation. The second focuses on the cognitive radio (CR). The third explains the concept of spectrum handoff. The fourth explains the importance of spectrum access to TWNs, CEO and TRAO. The fifth reviews existing mechanisms. The sixth describes the role of a unified architecture. The seventh is the conclusion.

2.1 Spectrum Demand, Allocation and Utilisation

The radio spectrum is a finite resource that is demanded by different technologies for improving user performance [1-2]. The spectrum demand of TWNs, CEO and TRAO are met by assigning them to different portions of the radio spectrum. The requirement of ensuring low interference spectrum allocation to different technologies requires the design of spectrum allocation mechanisms. This is because of technological advances in TWNs, CEO and TRAOs that necessitate having access to additional spectrum. However, the design of a new spectrum allocation framework requires knowledge of current spectrum utilisation. This is important to understand the necessary features to be incorporated in the new spectrum allocation framework. Spectrum usage measurements have been conducted in this regard.

Spectrum usage measurements show that the current approach of fixed spectrum allocation (FSA) limits spectrum utilisation [16-17]. The analysis in [16] shows that unused bands exist at different occasions at indoor and balcony locations. An analysis that extends [16] and considers spectrum usage of earth observations, TRAOs and TWNs is presented in [17]. Martian *et al.* [17] examine the mean occupancy of the (25-3400) MHz spectrum used for TWNs, earth observations and TRAOs. Analysis shows that the mean spectrum occupancy is 21% and 14 % in urban and rural areas,respectively.

The state of spectrum allocation between TWNs, TRAOs and CEO with FSA is as shown in Figure 2-1. TWNs, TRAOs and CEO are continuously evolving – with the emergence of previously unconsidered scenarios and new user requirements. The spectrum demand of TWNs, TRAOs and CEO is dynamic and not static. Hence, additional spectrum is continuously being allocated and reserved for TWNs, TRAOs and CEOs.

The reservation of spectrum for either TWNs, RAOs or CEO is unsustainable. This is because; as the spectrum demand of TWNs, TRAOs and CEO increases, less spectrum is available for other applications desiring spectrum access.

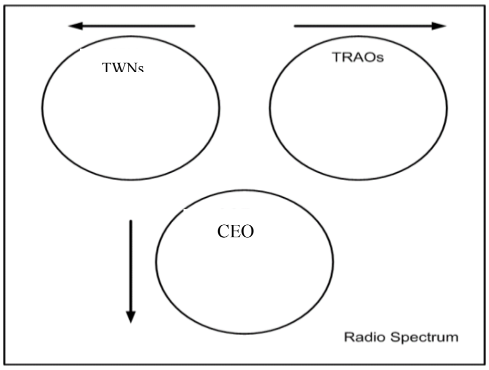

Figure 2-1: Status of application spectrum access with fixed spectrum access

Currently, the spectrum allocation mechanism being used is FSA. In FSA, a technology such as TRAO retains ownership of unutilised spectrum. This leads to spectrum underutilisation. It also creates a false notion of spectrum scarcity for users in other technologies (say TWNs) that require spectrum access. The challenge of false spectrum scarcity mitigates against the evolution of TWNs, CEO and TRAOs. Hence, the consensus is that the FSA causes spectrum underutilisation [23, 28-30]. Therefore, a new mechanism that overcomes the drawback of underutilisation in spectrum allocation is required. A mechanism that has been identified to be suitable in this regard is the dynamic spectrum allocation mechanism (DSA). In DSA, entities are spectrally agile and can execute spectrum handoff to use unutilised channels. DSA mechanisms enable interference reduction between TWNs, TRAOs and CEO. The interference reduction is realised by equipping users in TWNs, TRAOs and CEOs with spectrum handoff execution capability. The capability to execute spectrum handoff enables the concerned users to switch between different portions of the spectrum. Being environmentally aware, the CR can be used to realise spectrum handoff and DSA in TWNs, CEO or TRAOs.

Therefore, new techniques and technologies are needed to design a new spectrum allocation framework that enhances spectrum utilisation. The DSA is recognised to enhance the spectrum utilisation and requires the design of new technologies. However, the transition from the FSA to the DSA requires the incorporation of new technologies. An important technology in this regard is the cognitive radio (CR).

2.2 Technology for Improving Spectrum Utilisation - Cognitive Radio

The CR is a technology that can be used to realise DSA in TWNs, CEOs and TRAOs. It has been largely considered for improving spectrum utilisation and QoS in TWNs. In the TWN, the CR is an intelligent entity that is expected to improve spectrum utilisation and enhance user performance. The CR is capable of acquiring environmental awareness, making inferences using sensed results and reconfigure its transmission parameters accordingly [18-20]. The CR comprises two components, these are the hardware and software components [19]. The hardware component is realised by the reconfigurable software defined radio (SDR) [19]. The SDR can reconfigure its parameters such as the modulation, coding scheme and antenna orientation in real time. The SDR's operational parameters are dynamically adjusted using the sensing outcomes [20]. The SDR enables the CR to perceive its wireless environment and sense the state of the radio spectrum. Different sensing mechanisms such as energy detection, cyclostationarity detection and matched filtering [20] have been proposed for the CR.

The CR's software component are the algorithms that makes inference using the sensed results. These algorithms constitute the cognition engine [19]. The CR's cognition engine comprises mechanisms that enable the CR to make inferences and make decisions using sensed results. The reconfiguration decisions are made by the CR's learning algorithms and executed by the SDR hardware. Mackenzie *et al.* [19] present mechanisms that can be used in the CR's cognition engine. Examples of cognition engine mechanisms are genetic algorithms, artificial neural networks and case based decision makers [19].

Functionally, the CR can act as a PU or as an SU. As a PU, the CR uses the cognition engine to determine the suitable operational parameters in different scenarios. The CR PU uses the cognition engine to determine the parameters that enhance its QoS. The CR PU is not concerned with upholding the CPP because PUs have a higher spectrum access priority than SUs. In its role as an SU, the CR aims to improve spectrum utilisation, upholds the CPP and enhances its QoS. As an SU, the CR can change its channel and considers the wireless channel as an operational parameter. The ability of the CR to change its operating channel is called spectrum mobility. Spectrum mobility is executed by the spectrum handoff procedure in CR networks comprising PUs and SUs.

2.3 Cognitive Radio and Spectrum Handoff

The spectrum handoff capability is an important functionality for SUs. Spectrum handoff is the ability to discontinue transmission on a previously occupied channel and resume the transmission on another channel. The spectrum handoff event is triggered in the CR when continued transmission on a previously occupied channel becomes infeasible. Different network events can trigger the spectrum handoff depending on whether the CR is functioning either as a PU or SU. The PU changes its operational channel due to the occurrence of frequency selective fading on a previously occupied channel. In addition, user mobility can also trigger the execution of a handoff between TWN cells. The cellular handoff involves spectrum handoff when there is a change in the operating channel. The entrance of another PU cannot trigger spectrum handoff in a currently transmitting PU. The entrance of a PU triggers the exit of a transmitting SU. In the event that all channels are occupied by PUs, an incoming PU is not accepted. This is because there are no network resources.

SU spectrum handoff is triggered by all the events leading to PU spectrum handoff in addition to PU entrance. In the event of a PU entry, the SU exits its occupied spectrum. The exiting SU initiates spectrum sensing to look for another channel when PU entrance is detected. The SU executes spectrum handoff with the aim of upholding the CPP and enhancing QoS. The CR concept has been largely considered for TWNs because they currently have the largest spectrum usage [2]. Hence, the prevailing definition of spectrum handoff governs relations between PUs and SUs in TWNs only.

However, the future definition of spectrum handoff should transcend relations between PUs and SUs in TWNs. This is because of the increasing spectrum demand of emerging earth observations and TRAOs [1-2]. The increasing spectrum demand of TWNs, TRAOs and CEO necessitate a change in the definition of spectrum mobility. Spectrum mobility can be redefined as the execution of spectrum handoff between PUs and SUs in TWNs, TRAOs and CEO.

Spectrum handoff can be executed either reactively or proactively. In reactive spectrum handoff, the CR initialises spectrum sensing after continued data transmission or reception on a channel becomes infeasible. The CR using proactive spectrum handoff determines channels suitable at future epochs prior to exiting the currently occupied channel.

The realisation of proactive spectrum handoff requires learning mechanisms to enable the CR determine channels suitable for future use. An important technique that enables CRs to realise proactive spectrum handoff is spectrum prediction. Spectrum prediction enables CRs to determine transmit parameters on channels other than that being currently used for data transmission or reception. Examples of such parameters are channel state, channel idle duration, suitable transmit power and modulation.

Reactive and proactive spectrum handoff can be used in spectrum sharing models such as the underlay and interweave spectrum sharing model. In the underlay model, users can simultaneously transmit on the same channel provided that the cognitive priority protocol (CPP) is not contravened. The CPP is upheld by limiting user transmit power. A CR using reactive spectrum handoff and the underlay model determines the allowable transmit power after sensing an idle channel. The sensing is done after the continued use of the existing channel becomes infeasible. However, a CR using a proactive spectrum handoff determines the allowable transmit power via prediction. The prediction is done before the continued use of the existing channel becomes infeasible.

The interweave spectrum sharing model enables users to transmit on the same channel but not simultaneously. The users desiring to share spectrum transmit for an allowable time prior to the arrival of other users. A CR using reactive spectrum handoff observes the channel traffic patterns and determines allowable transmit time. The use of a proactive spectrum handoff enables the CR to determine the allowable transmit time for concerned channels apriori.

In the underlay spectrum sharing model, the transmit power limitation reduces the achievable signal to interference plus noise ratio (SINR). This limits the achievable user throughput in wide area coverage TWNs. The interweave spectrum sharing does not severely limit user transmit power and SINR. Hence, the interweave spectrum sharing model can enhance user throughput in wide area TWNs. This thesis focuses on proactive spectrum handoff and interweave spectrum sharing models.

2.4 Importance of Spectrum Allocation and Access to TWNs, TRAOs and Earth Observations

This section presents the entities in TWNs, TRAOs and earth observations that require radio spectrum access. It also discusses how technological advances lead to the evolution of these entities and the new user expectations. The spectrum access objectives and user expectations are also discussed.

Previously, spectrum handoff governed relations between PUs and SUs in TWNs because CRs has been largely considered for TWNs. In this context, spectrum mobility was limited to executing spectrum handoff between PUs and SUs in TWNs. However, the increasing spectrum demand of TRAOs and earth observations alongside TWNs necessitates a re-definition of spectrum mobility. Spectrum mobility is redefined as the execution of spectrum handoff between PUs and SUs in TWNs, CEO and TRAOs; and within PUs and SUs in either TWNs, CEO or TRAOs.

This section is divided into three parts. The first part discusses spectrum access for TWN entities. The second focuses on spectrum access for entities in TRAOs. The third explains spectrum access for entities in CEO.

2.4.1 Spectrum Access for TWN Entities

TWNs aim to provide their subscribers with communication services. TWNs can be classified as either infrastructure based or non-infrastructure based depending on the availability of a central coordination entity. TWNs can be classified on the basis of their coverage capacity. In terms of coverage, TWNs can be classified as local area networks, metropolitan area networks and wide area networks. Infrastructure and non-infrastructure based TWNs desire to access radio spectrum and enable their users to transmit data. Infrastructure based TWNs have a base station entity that manages communications between users while non-infrastructure based TWNs do have a base station entity.

In addition, infrastructure based networks can also have local, metropolitan and wide coverage. Examples of infrastructure based TWNs with local, metropolitan and wide coverage are IEEE 802.11, IEEE 802.16 and UMTS, respectively. The central entities in IEEE 802.11, IEEE 802.16 and UMTS are the access point, IEEE 802.16 base station and the Node B, respectively. Non-infrastructure based TWNs such as IEEE 802.15 and IEEE 802.16 adhoc mode do not have a wide area coverage.

This thesis focuses on spectrum access with the goal of improving user performance in TWNs. The considered TWNs are infrastructure based wide area coverage TWNs using licensed spectrum. This is because of the significant role of TWNs such as UMTS, LTE and LTE-A in mobile communications. TWNs such as UMTS, LTE and LTE-A comprise users i.e. subscribers and central entities such as the base station. The users in these TWNs transmit data to other users via the base station on the uplink. The base station sends user data and control signals to users on the downlink.

In infrastructure based wide area coverage TWNs, spectrum access is important for transmitting control signals and user data. Mobile TWN subscribers require spectrum access for high throughput applications such as online video, high throughput downloads and uploads. In addition, mobile TWNs should also have an improved spectrum utilisation. The spectrum utilisation can be improved by using more of the allocated spectrum for data transmission instead of signalling overhead.

TWNs subscribers make use of mobile terminals to transfer data to other users via the base station on the uplink. The mobile terminals used by the TWN subscribers can function either as PUs or SUs. PUs mobile terminals are end user devices that are previously served by TWNs prior to introducting SU mobile terminals. The SU mobile terminal incorporates CR capability and is introduced to enhance spectrum utilisation.

In TWNs, SUs are CRs that can have different capabilities. The CR can be either single mode or dual mode; based on the spectrum sensing and data transmission capability [20; 31-32]. CRs are expected to be capable of transmitting in heterogeneous wireless networks (HWNs). In this regard, CRs can be classified as having either multimode or multihomed capability. The spectrum access goals of the CRs (as SUs) with different capabilities is discussed as follows:

1) Single Mode CRs with proactive spectrum handoff: This type of CR can engage either in data transmission or spectrum prediction (leading to spectrum handoff). The spectrum handoff for the single mode CR involves switching between channels in a given radio access technology (RAT). The proactive spectrum handoff is executed using a well-trained learning mechanism. The learning mechanism has been trained using transmission patterns for prospective channels in future epochs.
2) Dual Mode CRs with proactive spectrum handoff: The dual mode CR can concurrently execute data transmission and spectrum prediction (leading to spectrum handoff). It executes spectrum handoff for channels in a given RAT. The proactive spectrum handoff requires a learning mechanism that has been trained using previous data transmission patterns.
3) Multimode Single Mode CRs: The CR can connect to multiple RATs but it only maintains connection to only one RAT at a time. This CR is expected to be capable of switching between the channels of different RATs. However, it cannot concurrently execute data transmission and spectrum prediction for channels in a given RAT.
4) Multihomed Single Mode CRs: The CR can concurrently connect to multiple RATs. It is capable of switching between the channels of different RATs. It can concurrently execute data transmission and spectrum prediction for channels in a given RAT.
5) Multimode Dual Mode CRs: The CR can connect to multiple RATs but it only maintains connection to only one RAT at a time. It is capable of switching between the channels of different RATs. In addition, it concurrently executes data transmission and spectrum prediction for channels.
6) Multihomed Dual Mode CRs: The CR can concurrently connect to multiple RATs. This CR is expected to be capable of switching between the channels of different RATs. In addition, it concurrently executes data transmission and spectrum prediction for multiple RAT channels.

These end-user devices are increasingly being adopted by TWN subscribers in form of smartphones with increasing technological capabilities. In addition, technological advances enable the design of more sophisticated end user devices. The proliferation of smart end user devices and increasing demand for high throughput applications necessitate allocating more spectrum to TWNs. However, the allocation of more spectrum increases spectral overlap between TWNs and TRAOs and earth observations. TRAOs and earth observations also have an increasing spectrum demand.

2.4.2 Entities Requiring Spectrum Access in TRAOs

Astronomy aims to study the underlying mechanisms of the universe by analysing signals radiated by objects in the universe. The studied objects are also called astronomy sources (ASs) and radiate the signals analysed by radio astronomers. Astronomy sources radiate different types of signals such as X-rays, gamma, optical radiation and radio waves. The signals radiated by ASs are received by ground based telescopes (GBTs) and analysed by the HPC. Telescopes can be located in ground or in space while the HPC is located on the ground. The increasing proliferation of TWNs and small satellites does not pose interference threats to X-ray, gamma and optical astronomy. However the increasing proliferation of TWNs and intersatellite links (ISLs) in small satellites pose interference threats to TRAOs.

TRAOs are conducted in observatories comprising GBTs and HPC. The GBTs receive signals from the observed ASs. The received signals are sent to the HPC for signal processing. The GBTs are exposed to the radio environment and are susceptible to interference from ISLs and TWNs. The HPC is not exposed to radio interference being perfectly shielded from interference via radio frequency interference shield.

The observation frequency of GBTs are also called spectral windows (SWs). Radio astronomers seek to study AS radiation at different SWs. The increased interest in TRAOs has also led to the construction of astronomy observatories. An example of a recently completed observatory is the Atacama Large Millimetre array (ALMA) inaugurated in 2013.

Relations between GBTs and the HPC are shown in Figure 2-2. As shown in Figure 2-2, the GBTs receive radio signals from ASs, the received radio signals are transmitted to the HPC. The GBT-HPC signal transmission is realised via optic fibre links (OFLs). The GBT-HPC link is bidirectional. It enables GBTs to send received ASs signals to the HPC. In addition, the HPC can also send configuration instructions to the GBT.

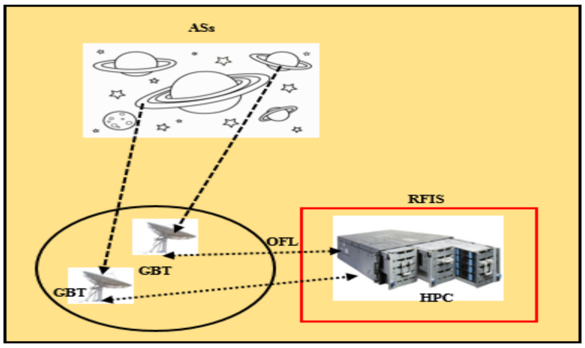

Figure 2-2: Interaction of components in terrestrial radio astronomy observations.

The interference between intersatellite links and terrestrial radio astronomy observations have been observed in [12; 33]. The observations in [12; 33] have not considered the role of ISLs in future small satellite networks. The increasing interference susceptibility between TWNs and TRAOs arise due to increasing population density. The increasing population density and the use wireless internet reduces the availability of potential TRQZs [34-38].

2.4.3 Role of Spectrum Access in Earth Observations

Commercial earth observations are conducted using networks that comprise space and ground segment. The space and ground segment hosts earth observation satellites and ground stations, respectively. CEOs execute their functions in the parameter observation, data downlink and data uplink stages.

1) **Parameter-Observation Stage (POS):** Earth observation sensors aboard the satellites and ground stations are used to acquire ECV data. These sensors observe ECV data in different portions of the radio spectrum. The spectrum-access demand of the POS is not considered; because this thesis does not analyse meteorological data.
2) **The Data-Downlink stage (DDS):** Satellites send their ECV data to the ground stations on the downlink. The X-band spectrum has been recognised to be suitable for the downlink transmission. This is because of the smaller antenna size accompanying the choice of this band. Hence, the satellite has a smaller weight. The choice of the X-band does not pose interference to the uplink and downlink in TWNs.
3) **The Data-Uplink Stage (DUS):** Ground stations capture data that are forwarded to satellites for availability at other locations. They should have access to high bandwidth channels, in order to obtain high uplink throughput. Ground stations can also be collocated with TWNs, in such a case they must not interfere with TWNs.

The desire to understand climatic patterns and use this knowledge to improve enterprise is the motivation for commercial earth observations. Earth observations is conducted via networks that comprise space and ground segments. The space and ground segment hosts earth observation satellites and ground stations, respectively. The earth observation satellites and ground station require radio spectrum access for monitoring and transferring ECVs to different locations.

Technological advances in the design of smart end-user devices for mobile TWNs have also influenced earth observation satellite design [39]. The smartphone's increased computing capacity has led to its incorporation in CEOs that use small satellites [39]. In addition, the SDR can be incorporated in small satellites [40-41] and mobile ground stations [41]. Small satellites have different subsystems. These are the power, attitude determination and control, on-board computing, payload and communication subsystems. The functions of these subsystems are:

1) **Power Subsystem (PS):** The PS provides electrical power to other subsystems. Its components include solar cells, electrical-distribution boards and rechargeable batteries. The PS keeps the small satellite alive in orbit.
2) **Attitude Determination and Control Subsystem (ADCS):** The ADCS comprises reaction wheels, magnetorquers and gyroscopes that maintain the small satellite's orbital position. It ensures that small satellites can perform station-keeping functions.
3) **Earth-Observation Payload Subsystem (EOPS):** The EOPS's components are used by small satellites to acquire earth-climatic variable (ECV) data. The EOPS composition depends on the small satellite development goals. EOPS components could be hyper-spectral imagers and cloud icing sensors. The EOPS requires spectrum access to observe the ECV.
4) **Communication Subsystem (CSS):** The satellite's communications is executed by the CSS. The CSS comprises the ISL, as well as the uplink and downlink modules. The ISL's downlink and uplink modules enable the inter-satellite, satellite to ground station and the ground stations to satellite communications, respectively. The uplink from the MGS to the CSS should have high throughput. The CSS requires radio spectrum access for ECV uplink, downlink and intersatellite communications via the ISLs. The increasing proliferation of TWNs pose interference to ground stations. In addition, ISLs pose interference risks to GBTs in the observatory exclusion zone.
5) **On-board Computing Subsystem (OCSS):** The OCSS is the brain; and it enables the small satellite to execute its algorithms. It receives and determines the small satellite's transmission parameters. The OCSS performs its functionalities by using inputs from other small satellites, CSS and the EOPS.

Small satellites used in CEOs can be either fractionated or non-fractionated [42-43]. In fractionated small satellites, the subsystems are located in different wirelessly linked units. In non-fractionated small satellites, the subsystems are located in a single unit and are not wirelessly linked. Being distributed, fractionated small satellites are more robust than non-fractionated small satellites. This is because the failure of a module does not lead to the loss of functionality in fractionated small satellites.

The architecture of a non- fractionated and fractionated small satellite are shown in Figures 2-3 and 2-4, respectively. Figure 2-3 presents the fractionated architecture for a small satellite designed using the CubeSat standard. The CubeSat is a small satellite that weighs approximately 1 kg. In Figure 2-3, the OCSS co-ordinates CubeSat operations; and it is connected to the other subsystems. The CubeSat subsystems are powered by the PS. The OCSS also checks the available PS power; and it determines whether there is sufficient power to drive CubeSat tasks. In Figure 2-3, all the subsystems are in a single CubeSat; and they are not connected wirelessly.

Figure 2-4 shows a fractionated CubeSat system. The fractionated CubeSat has the same subsystems as the non-fractionated CubeSat. In Figure 2-4, the subsystems are wirelessly linked. Each subsystem can have its own power sources; or it can wirelessly derive its power from the PS. The OCSS has a bidirectional link with the PS that helps the OCSS to derive power from the PS. The subsystems of the fractionated CubeSat are distinct CubeSats that are wirelessly linked. The structure shown in Figure 2-4 comprises five wirelessly linked CubeSats in a formation-flying configuration.

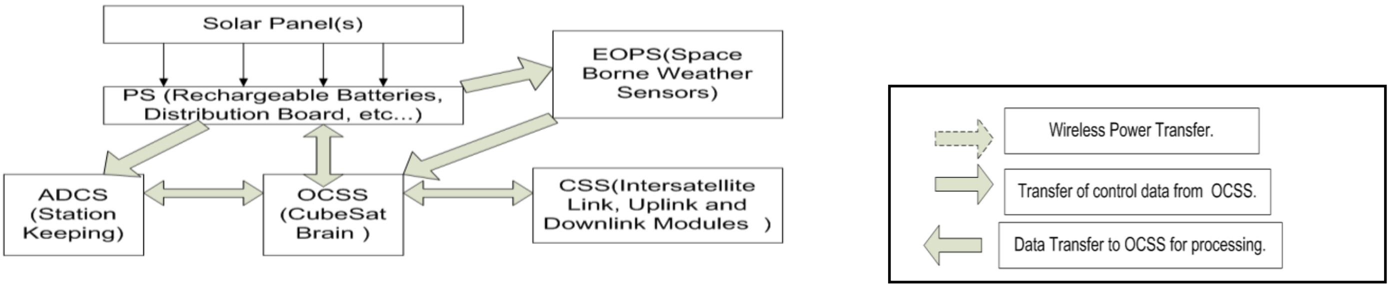

Figure 2-3: Non-fractionated CubeSat.

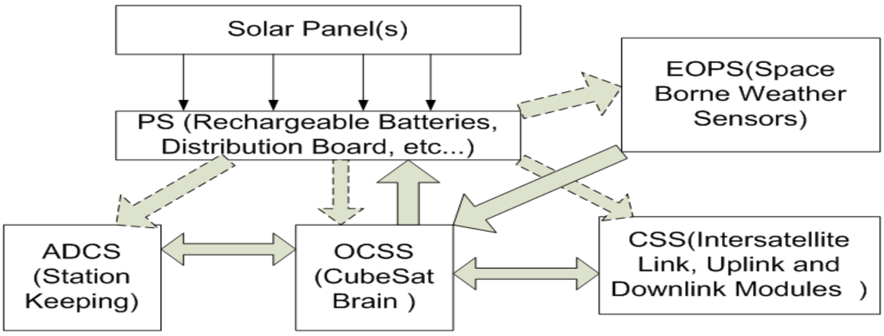

Figure 2-4: Fractionated CubeSat.

Both fractionated and non-fractionated CubeSats require spectrum access for data transmission [44-45]. Spectrum access is required for uplink, downlink and intersatellite communications. The relations between earth observation satellites and a mobile ground station is shown in Figure 2-5.

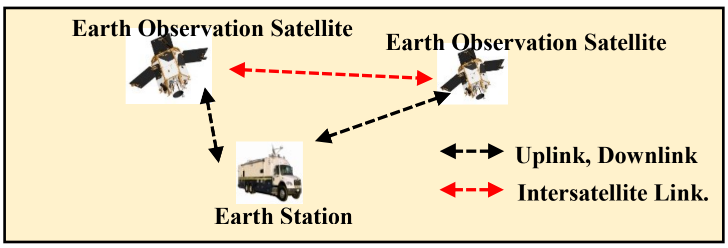

Figure 2-5: Interaction between earth observation satellites and ground stations.

2.5 Existing Spectrum Allocation and Performance Improvement Mechanisms

The previous sections have focused on the roles of the cognitive radio, spectrum handoff and the FSA. In addition, previous discussion describes relations between spectrum handoff and DSA's expectations. However, previous discussion has not reviewed existing interference reduction and performance improvement mechanisms in TWNs, CEO and TRAOs. The discussion is divided into three parts. The first, second and third parts discuss interference reduction and performance enhancement mechanisms proposed for TWNs, TRAOs and CEO, respectively.

2.5.1 TWNs – Interference Reduction and QoS Improvement Mechanisms

The CR was initially envisioned to enhance the QoS of TWN users [18]. It is also envisioned that the CR will use learning techniques to adapt to the surrounding wireless environment. In addition, the CR can be used to execute spectrum handoff. The CR uses intelligent mechanisms such as ANNs and HMMs for proactive spectrum handoff via spectrum prediction [23]. Spectrum prediction is the prior determination via trained intelligent mechanisms of the CR's transmission parameters on a TWN channel. The a priori determination of the CR's transmission parameters enables the CR to predict channel suitability. CR spectrum prediction is realised using mechanisms such as ANNs, HMMs and SVMs [19, 22-23].

This thesis considers the ANN as the learning mechanism of choice for CRs that are SUs in TWNs. The ANN is considered because of its efficient top down modelling approach [24]. It can be designed using different architectures such as multi-layer feedforward neural network (ML-FNNs), self-organising map neural network (SOM-NNs) and echo state network (ESNs). ANNs can be used to realise different learning objectives suitable for enhancing CR QoS and spectrum utilisation in TWNs. ANNs can be used for predicting user behaviour [24]. The prediction of user behaviour in [24] has been recognised to be capable of enhancing user QoS in TWNs [46]. ANNs can also be used for wireless channel identification [47] and channel prediction [48]. CRs use different ANNs architectures, such as ML-FNNs [22-23, 25-30, 48-49]. They can also use SOM-NNs [50-51] and ESNs [24, 47, 52]. CRs can also use algorithms that combine ANNs with other techniques, such as SVMs [51] and fuzzy logic [53].

The prediction of user's behaviour can enable the CR to determine transmission parameters for different user behaviour. Darmon *et al.* [24] propose using an ESN – for predicting user behaviour. The ESN is considered because of its low computational cost. It has also been considered for wireless channel identification [47]. The ANN is a learning mechanism that can be used for spectrum prediction and executing proactive spectrum handoff. A scenario showing the execution of proactive spectrum handoff by SUs in single RAT TWNs is shown in Figure 2-6. In Figure 2-6, it is assumed that the SU uses a well-trained ANN as the proactive handoff mechanism. The ANN enables the CR to predict its allowable channel connection duration. It is also assumed that the CR selects the channel with the longest interference free connection duration.

Figure 2-6 shows two scenarios that demonstrate the role of proactive spectrum handoff between PUs and an SU in the TWN. The scenarios comprise a TWN base station (BS), PUs and an SU. In the scenario on the left, PU 1 and PU 2 use channels c_1 and c_3, respectively. PU 1 and PU 2 are at the epoch of completing data transmission. PU 3 is an incoming PU that triggers SU proactive spectrum handoff. PU 1 and PU 2 are at the epoch of completing their data transmission. However, PU 3 does not wait for them. This is because PU 3 has an higher spectrum access priority than the SU on c_2. The SU predicts the allowable communication duration on c_1 and c_3 as t_1 and t_3, respectively. c_1 and c_3 have equal bandwidth and $t_3 > t_1$. Prior to executing the spectrum handoff, the SU is located on c_2. The SU detects incoming PU 3. However, before exiting c_2 the SU has predicted its allowable connection duration on c_1 and c_3. Being aware of the predicted allowable connection duration on c_3. The SU executes a spectrum handoff and continues its data transmission on c_3 with a longer connection duration. The scenario on the right presents the network after the SU has executed proactive spectrum handoff. The SU has executed the spectrum prediction procedure and selected channel c_3 with the longest predicted connection duration.

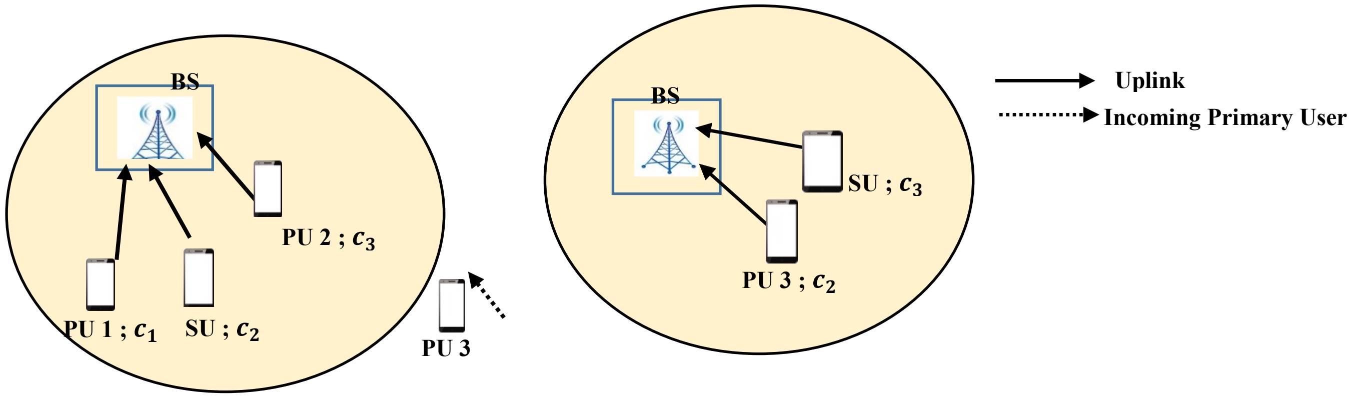

Figure 2-6: Role of spectrum handoff in terrestrial wireless networks.

The execution of proactive spectrum handoff by SUs in HWNs is shown in Figure 2-7. Figure 2-7 shows the role of proactive spectrum handoff in HWNs. The HWN comprises two RATs with base stations BS 1 and BS 2. BS 1 supports PU 1 and SU transmission on channels c_1 and c_2, respectively. BS 2 supports the transmission of PU 2 and PU 3 on channels c_3 and c_4 , respectively. The overlapping of the coverage of BS 1 and BS 2 results in the HWN. The incoming PU selects BS 1 thereby leading to the exit of the SU from c_2. The exiting SU predicts its connection duration on channels c_1 , c_3 and c_4. In Figure 2-7, it is assumed that PU 1, PU 2 and PU 3 are at the epoch of completing their data transmission. The exiting SU predicts the allowable connection duration for c_1 , c_3 and c_4 and selects the channel with longest connection duration.

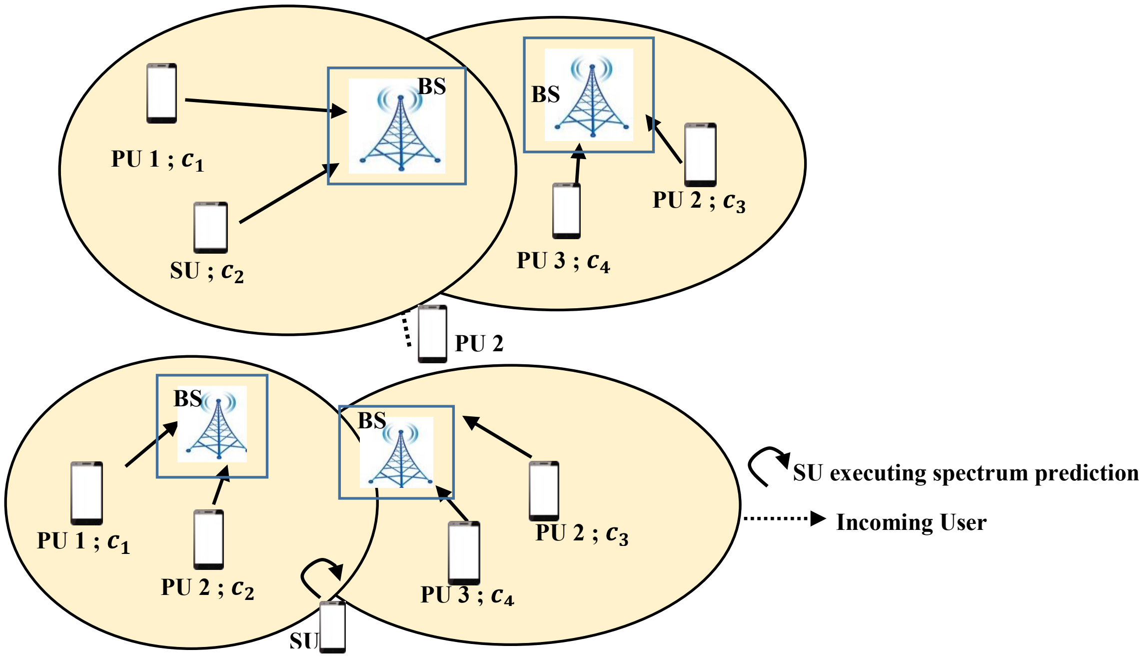

Figure 2-7: Spectrum handoff in heterogeneous wireless networks.

CR spectrum utilisation and QoS improvement can also be enhanced by reducing TWN overhead. In [47], the use of the ESN enables the CR to infer the network state with minimal control channel information. The use of the ESN in [47] reduces the overhead, enhances spectrum utilisation and CR QoS. CR ANN spectrum prediction also enables the CR to exploit transmission opportunities [48-49]. Statistical models have been developed to model the channel state, the idle duration and the throughput [48]. These models can be used to simulate, develop and investigate predictive ANN models. Shahid *et al.* [48] developed the channel state and idle time predictor scheme (CSIT). CSIT is an ANN predictive mechanism that enables SUs make opportunistic use of idle spectrum in LTE-A. A summary of CR ANNs architectures suitable for executing tasks that enable CR spectrum prediction is shown in Table 2-1.

Table 2-1: Overview of artificial neural networks Architectures useful for cognitive radio learning

Architecture	Strength(s)	Challenge(s)
ML-FNN[22-23, 25-30]	The ML-FNN can predict future channel occupancy from datasets for GSM, 3G and the TV white space. The prediction of future channel occupancy enables the realisation of proactive spectrum handoff. In addition, the ML-FNN is scalable and well-studied.	Spectrum prediction is challenging in environments where different parameters are available at different time.
ESN [47,52]	The ESN is used in applications requiring channel classification with minimal use of control overhead by the CR. This reduces the signalling overhead. The ESN is conceptually simple compared to HMMs. It has low computational costs since only the output weights are trained.	Dynamic wireless environments incur high signalling to realise rich reservoir for future prediction.
SOM-NN [50-51]	CR QoS Enhancement: The SOM-NN is used for predicting the bit rate. It is suitable for advanced CR learning in dynamic wireless environment.	Choice of learning mechanisms suitable for different scenarios in dynamic environment for CR learning is required.
ML-FNN + Reconstruction algorithms [29]	Hybrid scheme is created to ensure that CRs select ANNs for predefined scenarios. Enables CR to, classify, predict and make decisions without limitations of rule base.	Learning mechanism cannot reconfigure to accommodate outliers in new scenarios.
SOM-NN + SVM [51]	Hybrid mechanism enhances CR classification capability. The joint use of SOM-NNs and SVMs enables the formation of fine decision regions.	Training mechanism needs to ensure that SVM regions remain distinct without increasing confusion probability.
Neuro-Fuzzy (ML-FNN+ Fuzzy Logic) [53]	Pre-processed user preferences are formulated to meet CR objective and train ML-FNN. Fuzzy logic handles uncertainty in training data.	Scalability of fuzzy logic rule base becomes challenging when multiple inputs are handled.

The discussion in this section focuses on the suitability of ANNs as CR-learning algorithms in TWNs and HWNs. ANNs have been considered for sensing [22], spectrum prediction [23,28-30,48-49,53] and classification [47, 51]. They are also suitable for RAT selection [50, 54-55], user-behaviour prediction [24, 56] and antenna design [57-58]. ANNs are computationally flexible; and they can be used for general purposes as function approximators. This makes them useful to handle spectrum-prediction tasks requiring different parameters.

The CR is also expected to be capable of executing spectrum handoff in HWNs. In an HWN, the CR is expected to select the best channel in a suitable candidate RAT. The determination of a suitable channel aims to enhance QoS and uphold the CPP. This invokes a spectrum handoff procedure. The execution of spectrum handoff by CRs in HWNs should enhance spectrum utilisation and CR QoS. The expected role of proactive spectrum handoff for SU is discussed in [49]. In [49], CR spectrum prediction enables opportunistic use of TV spectrum. An intelligent RAT selection mechanism that uses learning mechanisms is presented in [54]. The mechanism presented in [54] is suitable for CR PUs and not SUs. This is because Rakovic *et al.* [54] have not considered spectrum usage parameters. The discussion in [54] implicitly invokes a spectrum handoff because TWN RATs use different portions of the radio spectrum

ANNs can also be used for spectrum prediction in HWNs. CR spectrum prediction can be used to address challenges in HWNs. A challenge for CRs in HWNs is that of RAT selection [59]. RAT selection algorithms can be either cognitive or non-cognitive [54]. Cognitive RAT selection algorithms are more dynamic than non-cognitive RAT selection algorithms. CRs incorporating cognitive RAT selection algorithms can use ANNs for RAT selection. In HWNs, CR SUs should select the RAT and channel that enhances CR QoS, while upholding the CPP. The scheme in [50] is a cognitive RAT-selection mechanism that uses the trained SOM-NN. Non-cognitive RAT selection algorithms use pre-defined inputs and policies that are not adjustable when sub-optimal or wrong decisions result [54].

Rakovic *et al.* [54] use the Hopfield neural network and consider ten parameters. However, they have not considered parameters related to CR SU spectrum access. Hence, the mechanism is not suitable for SUs. RAT selection in HWNs requires that CRs should select the RAT that best satisfies user QoS and improves spectrum utilisation. RAT selection algorithms consider different criteria to enable CRs select the best RAT. A CR SOM-NN predictor model is presented in [50]. The CR selects between the IEEE 802.11b and the 802.11g modes based on the predicted bit rate. The SOM-NN is considered; because it supports unsupervised training. Unsupervised training is suitable for autonomous CR learning. The training enables the CR to select the best radio configuration. Tsakgaris *et al.* [50] considered that the IEEE 802.11 b and IEEE 802.11g modes use the 2.4 GHz spectrum. The selection between the IEEE 802.11b and IEEE 802.11g RATs assumes ideal spectrum access for CRs. Ideal CR spectrum access is obtainable when CRs are PUs, or when there is zero PU activity. The training in [50] is unsuitable for CR SUs seeking to predict allowable connection duration on RAT channels. Tsakgaris *et al.* [50] also presented the SOM-NN training results. The SOM-NN has an average training duration of 6 seconds; and it uses 0.4 MB.

Abbas *et al.* [60] propose a RAT-selection mechanism for an HWN comprising IEEE 802.11 and 3G RATs. The proposed RAT-selection mechanism considers seven parameters; and it is designed by using a rule base. The presented mechanism advances [54] by using inputs that are known to mobile users. The rule-based RAT selection algorithm is unsuitable for SUs because it does not explicitly consider the role of spectrum prediction. Moreover, the rule base has scalability challenges.

In [50,54,59- 60], it is implicitly assumed that the CR has access to the RAT selection parameters. Hence, RAT selection proceeds on the basis of the availability of a repository, where RAT selection parameters are held. Chen *et al.* [61] proposed a cross-layer algorithm that explicitly considers the role of a repository for CR RAT selection. The selection decision is made by using information from multiple layers that describe the user's requirements. The cross-layer determination of the best RAT for a given application is done by using information available in the cognitive repository. The cognitive repository's contents are analysed to select the best RAT. It is assumed that the cognitive repository has all the required parameters. The mobile terminal using the mechanism in [61] monitors and obtains information on the network status. It filters the required information from the obtained information. It can be inferred that the mobile terminal obtains network status information from another network entity.

The transfer of information from another network entity to the mobile terminal is susceptible to wireless channel impairments. However, RAT-selection parameters are assumed to be available to the subscriber in [61]. RAT selection becomes challenging when required RAT selection information is not available.

Haldar *et al.* [62] propose a RAT selection mechanism for an heterogeneous cognitive wireless network. The mechanism scans the radio environment, analyses the signal strength of RATs and uses the results for analysis to acquire handoff awareness. In [62], user applications are assigned channels via a application classification procedure. The application classification procedure increases the latency for delay-intolerant applications when CRs use multiple applications. This is because the approach couples application classification, network selection and channel assignment. Therefore, it is important to design algorithms that overcome this drawback.

Rao *et al.* [55] present the always best-connected and served RAT selection paradigm. They recognise that ANNs are suitable for cognitive RAT selection. This is because ANNs can be used to make decisions, when the situation is unknown to selection, then heuristics arise. Similar to the perspective in [61], the importance of a repository is identified to be important for designing RAT-selection algorithms [55].

Though the discussion has focused on using learning mechanisms for RAT selection, they can be used for other tasks. The tasks are those that meet the objectives of low interference spectrum access and improve user QoS. The applications of learning mechanisms in CRs in TWN is shown in Table 2-2.

Table 2-2: Application of learning mechanisms in cognitive radios.

	Mechanism	Spectrum	Training Parameter	Objective
Bai *et al.* [22]	Back Propagation neural network	80-120 MHz	Power time series samples of Agilent N9020A.	Interference Reduction: The ML-FNN is used to predict the energy detection decision threshold. PU-SU interference is reduced by improving the correct sensing probability in energy detection.
Shahid *et al.* [48]	Multilayer feedforward neural networks.	Licensed Spectrum; LTE-Advanced (LTE-A).	Data sets of PU arrivals, using time slot information and allowable connection duration.	Interference reduction and enhancing QoS: Predicting the future channel state and idle duration for LTE-A channels. The proposed mechanism is called channel state and idle time (CSIT). CSIT improves CR LTE-A QoS.
Tsakgaris *et al.* [50]	SOM-NNs for candidate radio configuration selection and bit rate prediction.	Unlicensed – 2.4 GHz ; RATs – IEEE 802.11b, IEEE 802.11g	Received signal strength indicator, input and output errors, received and sent packets, achievable bit rate.	QoS Improvement: The mechanism uses the SOM-NN to improve CR QoS by selecting the RAT via a proactive spectrum handoff. The RAT with the highest predicted bit rate is selected.
Shaswar *et al.*[51]	SOM-SVM for RAT Standard classification.	Unlicensed ; Licensed WCDMA,IEEE 802.11a	Power time series data	Enhancing spectrum utilisation by reducing signalling overhead: RAT classification. The mechanism is cognitive and the SOM-NN can accept new inputs for the classification process.
Rakovic *et al.* [54]	Hopfield-Neural Network	Unlicensed	Application bit rate, application delay, type of the application, available capacity from serving network, serving network delay, available target network capacity, target network delay, handover trigger, mobile speed, SINR	Enhancing QoS: RAT Selection between IEEE 802.11 and IEEE 802.16. The Hopfield neural network uses dynamic input-output relations and aims to improve the user QoS.
Abbas *et al.* [60]	Trained Rule Base for RAT selection	Unlicensed, Licensed 3G , IEEE 802.11	Availability of 3G and IEEE 802.11 networks, signal strength, Data size, battery life, speed, location and type of application.	Enhancing user QoS: Select RAT with minimum energy consumption and best user QoS. The algorithm is cognitive due to the learning components. The rule base does not flexibly accept new selection parameters.
Chen *et al.* [61]	Fuzzy evaluation and quantum genetic algorithm.	Unlicensed, Licensed IEEE 802.11 and UMTS	Throughput, Jitter, Rate, Session Completion, Average Delay and end to end loss rate.	Enhancing User QoS: Select RAT with best QoS. The algorithm is non-cognitive, does not involve learning; and can accommodate flexible number of parameters.
Lashkar *et al.* [53]	Fuzzy Neural Approach	Licensed Spectrum and designed to be suitable for any RAT.	Spectrum Efficiency, SU Mobility and distance between primary user and secondary user.	Enhancing spectrum utilisation and user QoS: Spectrum mobility using fuzzy neural approach. Neural network is trained using fuzzified inputs. It is cognitive and uses learning.

Table 2-2 shows that ANNs have been widely considered for preventing interference between PUs and SUs in TWNs. ANNs have also been found suitable for executing proactive spectrum handoff via spectrum prediction.

2.5.2 Interference Reduction and Performance Improvement Mechanisms in Earth Observations

The increasing spectrum demand of TWNs have led to the occurrence of scenarios where TWNs are allocated earth observations spectrum. In these scenarios, the TWNs interfere with the meteorological ground radar. Incidences of such interference have been observed in [63-64]. Small satellite proliferation [5-11] has also led to the evolution of CEOnetworks. Previously, the FSA has been used for spectrum allocation between CEOs with the aim of reducing TWN-CEO interference. However due to the increasing spectrum demand, TWN subscribers are now using spectrum initially meant for earth observation ground stations [63]. This has led to the design of mechanisms that reduce interference between TWNs and earth observations ground station. Mechanisms that address interference in similar scenarios in satellite applications can be found in [65-68].

Tercero *et al.* [66] examined a scenario where IEEE 802.11 TWN users and ground meteorological radar share the 5.60-5.65 GHz band. In [66], the ground meteorological radar and the IEEE 802.11 are the PU and the SU, respectively. The proposed mechanism enables dynamic spectrum access. Investigations also show that the proposed mechanism enhances the SU transmission probability compared to the existing dynamic frequency selection. In the proposed mechanism, IEEE 802.11 subscribers use radar rotation information to opportunistically use the idle spectrum in the 5.60-5.65 GHz band. This consideration is not suitable for wide area networks TWNs with a larger coverage than the IEEE 802.11. The coverage radius of TWNs exceeds the radius of the ground meteorological radar.

Deng *et al.* [67] propose a space digital filter that enables radar performance to be unaffected by interfering TWNs. The scenario considered in [67] comprises MIMO radar and TWN subscribers. Subscribers interfere with the main and the side lobes of the MIMO radar system. The filter reduces the interference effect of TWNs on the radar's main and side lobes. It becomes active after the completion of matched filtering on the signals received at the MIMO radar. The interference reduction space-digital filter is located in the MIMO radar. The filter enables the elimination of TWN interference from the main and side lobes. However, the filter focuses on interference cancellation and not enhancing spectrum utilisation.

The mechanism in [67] focuses on interference cancellation and ensures that the ground segment has an high SINR. The enhancement of the SINR does not imply that ground stations have accessed additional bandwidth. The ground segment throughput can be further improved by accessing additional bandwidth at enhanced SINR.

The mechanisms in [66-67] have not considered CR spectrum sharing to prevent TWN-CEO interference. This is because the CR was initially proposed for improving user QoS, spectrum utilisation and avoiding interference in TWNs [18]. However, the potential of the CR to enhance spectrum utilisation in satellite applications has also received attention in research. A notable initiative in this regard is the cognitive radio for satellite initiative (CoRaSat) presented in [65].

Liolis *et al.* [65] present the CoRaSat initiative, an FP7 project that incorporates the CR in satellite communications. The CoRaSat initiative is considered important because it identifies the CR's potential to enhance spectrum utilisation in satellite applications. Earth observations are an important category of satellite application. CoRaSat reduces interference-free spectrum allocation strategies for satellite communications in the non-geostationary and geostationary orbit. It outlines the challenges and benefits associated with using different CR spectrum sharing models in satellite applications. Though, CoRaSat has not explicitly presented strategies for earth observations; it identifies the potential of CRs to improve satellite applications.

The interference between radar and TWNs also occurs in the licensed S-band. Heuel *et al.* in [68] examine the interference between S-band air traffic control radar and the LTE TWN. The resulting interference degrades LTE throughput and can damage the S-band radar. A CEOxistence framework, using DSA cognitive radar, has been identified as being useful. The co-existence framework enables the LTE to co-exist with S-band radar. Therefore, a CR-based spectrum-sharing framework is required. The framework protects S-band meteorological radar from the interfering LTE-A TWN.

The discussion in [40] extends [68] by considering the suitability of the SDR in reducing interference. In [40], the SDR is considered suitable for protecting small satellite applications from interference. The SDR can also be incorporated in the ground station. The SDR aboard the ground station is expected to be capable of predicting spectrum demand. This prediction requires that the ground stations should be equipped with intelligent mechanisms. In addition, the discussion here assumes that the ground station does not interact with TWNs. Hence, the increasing spectrum demand of TWNs and the resulting interference observed in [63-64] has not been considered.

In [41], Maheshwarrappa *et al.* present an SDR architecture to support multi-satellite communications. The discussion in [41] extends [40] by considering the incorporation of SDR transceivers in mobile ground stations. The communications requirement in this case involves data transmission between multiple satellites and ground stations. The communications is realised via SDR transceivers that can be used on mobile ground stations and satellites. The presented transceiver can transmit on the (70 – 6000) MHz spectrum. The S-band lies within the considered spectrum. Hence, it is important to consider the interference that arise between mobile ground stations and TWNs in the S-band spectrum.

A co-existence scenario that results in interference between TWNs and earth observation satellites is shown in Figure 2-8. The scenario in Figure 2-8 comprises the LTE TWN and the earth observation network. In Figure 2-8, there is an overlap between the coverage areas of earth observation satellites and the LTE eNode B (eNB). The LTE comprises the eNB and LTE subscribers i.e. TWN users. The earth observation network comprises two earth observation satellites and a mobile ground station (MGS). The subscribers and the ground station are engaged in uplink transmission with the eNB and the satellites, respectively. The ground station to satellite transmission is being done via the S-band to obtain an enhanced throughput. The S-band is suitable for uplink transmission [40]. In addition, the ground station is assumed to have a functional link budget. The ground station-satellite uplink interferes with the uplink of LTE subscribers 1 and 2.

The incorporation of techniques that enable DSA in LTE subscribers or the mobile ground station is useful in preventing interference. The PUs and SUs could either be the LTE subscribers or the ground station. The incorporation of a proactive spectrum handoff technique in the ground station enables it to predict LTE channel suitability. In addition, the use of spectrum prediction can enable the ground station to share spectrum with LTE subscribers.

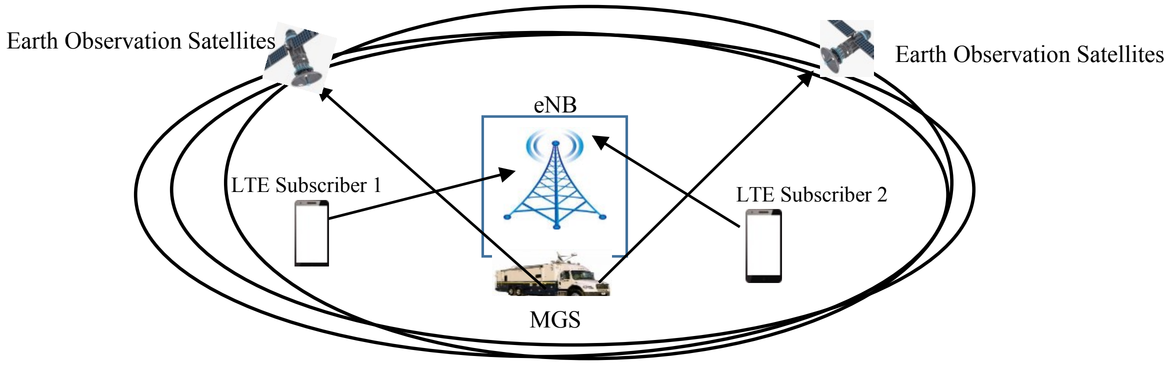

Figure 2-8: Interference between terrestrial wireless networks and commercial earth observations.

The increasing spectrum demand of TWNs poses interference risks to other technologies requiring spectrum access. Examples of such technologies are air traffic control and meteorological ground station radar. Different interference reduction mechanisms have been proposed to prevent interference in scenarios where TWNs and earth observation radar CEO exist. A summary of existing interference reduction mechanisms are presented in Table 2-3.

Table 2-3: Interference reduction mechanisms for terrestrial wireless network - earth observation existence.

	Mechanism	**Aims and Objectives**	**Challenges and Future Prospects**
Tercero *et al.* [66]	Dynamic frequency selection mechanism	Dynamic frequency selection reduces interference between IEEE 802.11 users and meteorological ground radar in the 5.60-5.65 GHz spectrum. The ground radar is the PU while the IEEE 802.11 subscriber is the SU. SUs use radar rotation information for spectrum sharing.	Proposed mechanism improves the utilisation of the 5.60-5.65 GHz unlicensed spectrum. The considered IEEE 802.11 also has local coverage and not wide area coverage. It has not considered the interference that arises between wide area TWNs and meteorological ground station in licensed spectrum.
Deng et al. [67]	Space domain digital filter	The proposed filter reduces interference between MIMO Radar and TWN users. It removes interfering TWN signals from the MIMO radar.	The filter reduces MIMO radar signal bit error rate but does not improve spectrum utilisation.
Heuel *et al.* [68]	Cognitive Radar	The cognitive radar is identified to be suitable for reducing interference between LTE TWN and airport radar. The scenario has been considered to be of interest to CEOs because meteorological ground radar can also be located in TWN coverage zones.	Additional consideration is required to design cognitive mechanisms that prevent interference between TWNs and CEOs.
Maheshwarrappa *et al.* [40]	SDR incorporation for small satellites and ground stations.	The research proposes using SDR in small satellites to host intelligent mechanisms. The intelligent mechanisms enable proactive spectrum handoff on the ground station by predicting the future spectrum demand of satellites.	Further consideration is needed to design intelligent mechanisms that predict future satellite spectrum demand. In addition, the discussion has not focused on reducing interference between TWNs and CEOs.
Maheshwarrappa *et al.*[41]	SDR incorporation in ground stations in multi-satellite constellations networks.	The SDR is incorporated in mobile ground stations that communicate with multiple small satellites. The mobile ground station is expected to transmit in the (70-6000) MHz band. TWNs that use licensed and unlicensed spectrum lie in the mobile ground station's operating band.	The mobile ground station poses interference risks to TWNs that use spectrum in the (70-6000) MHz band. Additional work is required to design suitable interference reduction mechanisms.

2.5.3 Terrestrial Radio Astronomy – Spectrum Allocation and Interference Reduction Mechanisms

The interference between TWNs and TRAOs arise due to their increasing spectrum demand. The factors necessitating increased spectrum demand are high throughput applications in TWNs and observing additional SWs in TRAOs. TRAO spectrum allocation is conducted with the aim of ensuring that GBTs are not susceptible to interference. Hence, TWN users are disallowed from transmitting on bands allocated to TRAOs

[69-72]. This method of spectrum allocation is synonymous to the FSA regime. However, the proliferation of TWNs has been recognised to pose interference risks to TRAOs [2, 13]. New mechanisms are required to protect GBTs used in TRAOs from TWN interference. The new mechanism should also satisfy two requirements. First, it should ensure that the increasing spectrum demand in TWNs are met. Second, it should enable interference free co-existence between TWNs and TRAOs. This goal can be realised by using the DSA instead of the FSA.

An additional factor that increases TRAO susceptibility to TWN interference is the use of converted earth stations [14, 73-76]. The converted earth stations have been previously used for satellite communications. These earth stations are being converted due to the increasing use of optic fibre links for intercontinental internet access. The conversion of unused earth stations to GBTs is an approach that reduces TRAO costs. Converted GBTs are susceptible to interference when TWNs have been installed in their locations prior to the conversion.

TRAOs also experience interference from ISLs [12]. ISLs are used for enabling communications between satellites [33, 40]. Hence, the interference susceptibility of TRAOs is due to the proliferation of small satellites and TWNs. However, the CR as a technology for enabling proactive spectrum handoff has not received wide consideration for spectrum access in TRAOs.

Spectrum allocation for TRAOs is examined in [69-70]. Pankonin *et al.* [69] and Waterman *et al.* [70] advocate radio-spectrum reservation (like FSA) for TRAOs. This reservation limits spectrum utilisation. The feasibility of frequency sharing is considered from a regulatory perspective in [71]. Isnard [71] views frequency sharing as a multi-level collaborative effort requiring the participation of the international telecommunication union and regional-spectrum regulators. The L-band is identified as the band for the intended spectrum sharing. Interference reduction in TRAOs is considered as an important issue by different regional spectrum regulators [72]. The goal of interference reduction in TRAOs is achieved by locating GBTs in terrestrial radio quiet zones (TRQZs).

The suitability of TRQZs as an interference reduction tool is threatened by increasing population density. The increasing population density is accompanied with higher demand for TWN access [34, 36-37] by more subscribers. Though GBTs are located in TRQZs, TRAOs are susceptible to interference from satellite applications such as CEOs. The interference arises from the ISL used for satellite – satellite communications. In addressing this interference challenge, Gergely [12] proposes that satellites should be restricted from TRQZs. The restriction enforces the use of the allocated radio spectrum by TRAOs only. This approach prevents the ISL from sharing the spectrum with GBTs. Hence, it is synonymous to the FSA regime. This restriction requires the re-design of satellite orbits to consider TRAO observation requirements. The re-design of satellite orbits especially in the low earth orbit cannot be realised using only CRs. The issue of orbital re-design is not considered in this thesis because the focus is on using CRs to reduce interference and enhancing spectrum utilisation.

The occurrence of interference between TRAOs, TWNs and satellite networks requires a new interference reduction mechanism. This mechanism should enable TRAOs to access the spectrum without preventing other applications from achieving their spectrum access objectives. Such a goal can be achieved if there is CEOxistence. The desired CEOxistence can be realised via proactive spectrum handoff mechanisms that enable DSA. The required mechanisms can be designed using the CR.

The CR has not been widely considered for achieving DSA in TRAOs when compared to TWNs and CEOs. Bentum *et al.* [13] propose using CR underlay spectrum sharing model for low interference coexistence between TRAOs and TWNs. However, the analysis shows that the CEOxistence is infeasible. This is because of the low power of the TRAO signal compared to that of the TWN signal. In addition, the received signals in TRAOs cannot be controlled being received from ASs. Furthermore, a reduction of the TWN signal power to ensure CEOxistence makes data transmission infeasible.

The SDR has been found to be capable of enhancing TRAOs. Behnke *et al.* [77] has identified that the SDR is capable of enhancing TRAOs. The SDR's suitability is due to its advanced spectral processing capability. The discussion in [77] recognises that the SDR has an excellent out-of-band rejection capacity. Being the hardware component of the CR, the SDR can be furnished with intelligent mechanisms to realise DSA in TRAOs.

A new spectrum allocation framework is required to reduce interference between (TRAOs and TWNs) and (TRAOs and ISLs). The new framework should reduce interference, uphold the CPP and enhance the spectrum utilisation. The new framework should also realise the end goal of spectrum utilisation. The end goal of spectrum utilisation is to enhance user performance.

The new framework requires an architecture that incorporates DSA and jointly considers the spectrum access objectives of emerging technologies. Such an architecture unifies the spectrum access goals of TWNs, CEOs and TRAOs and is presented in the next section.

2.6 Unified Architecture for Enhancing Emerging TWNs, TRAOs and Earth Observations

In the review above, it can be seen that TWNs, CEOs and TRAOs pose interference risks to each other. Scenarios, where interference occurs between TWNs and earth observations can be seen in [66]. In addition, technological advances, such as those described in [78] and [79] , make the scenario in [65] applicable to earth observations also. The evolution of earth observation services as noted in [79, 80] has also given a reason to consider interference between the TWNs and CEOs. Fish *et al.* [79] notes that the knowledge derived from earth climatic variables from commercial earth observations should be re-packaged to improve the mass appeal. The view of improving the mass appeal of CEOs is also corroborated by Zhou *et al*. [80]. In [80], mass appeal is enhanced by allowing real time users to select sensor parameters and extract desired information from earth climatic variables.

Interference-reducing solutions are required for these scenarios. Interference reduction can be realised by designing an appropriate spectrum access framework. The state of spectrum allocation between TWNs, earth observations (EOs) and TRAOs as perceived from existing work is shown in Figure 2-9.

Figure 2-9 shows spectrum access conflicts that occur between TWNs, earth observations (EOs), TRAOs and satellite communication network (SCNs). It demonstrates the relationships between EOs, TRAOs and SCNs, as regards their spectrum-access objectives. The interference pairs that are recognised in Figure 2-9 are TWNs-EOs [63, 66] and SCNs–TRAOs [12,33]. The TWNs-CEOs interference pair describes a scenario where ground stations are collocated with TWNs, such as LTE.

Interference also arises for the SCNs-TRAOs pair; and this concerns SCNs located in the low earth orbit (LEO). The SCN uses ISLs transmitting in either the L-band (1-2 GHz), S-band (2-4 GHz) or the C-band (4-8 GHz). TRAOs also require access to these bands as SWs – to observe ASs. An interference-reduction framework is required when SW and ISLs require access to the same band at the same instant. Additional pairs that are considered currently infeasible in Figure 2-9 are SCNs-EOs and EOs-TRAOs. In SCNs-EOs, interference is not considered to arise between earth observation and ground stations and mobile satellite subscribers. This is because mobile satellite communication's operational frequencies are known and avoided by ground stations. In addition, earth-observation ground stations are located outside the TRQZ. Furthermore, the earth-observation data downlink and uplink occurs far from the TRQZ. Therefore, earth-observation signals have a null field strength at the TRQZ, due to the free space loss.

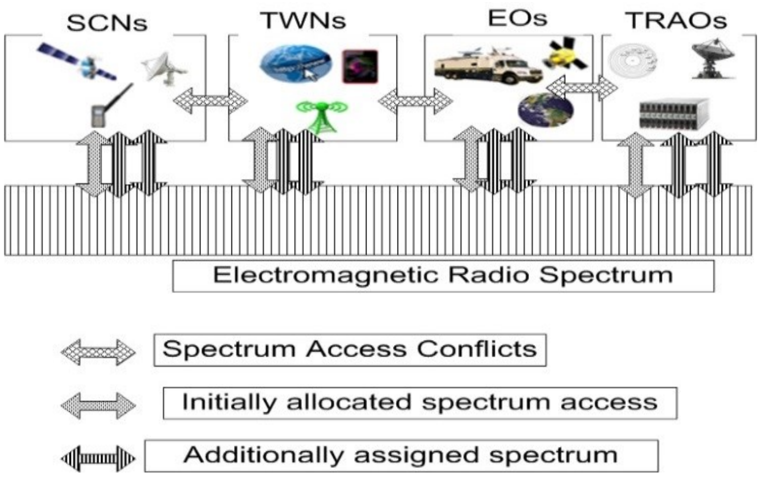

Figure 2-9: Spectrum access and conflicts between wireless communications, earth observation and terrestrial radio astronomy.

Currently, the radio spectrum is separately allocated to TWN users and entities in CEOs and TRAOs. The allocated radio spectrum remain unused even if the concerned entities do not desire to use the allocated spectrum. This manner of spectrum allocation called fixed spectrum allocation (FSA) leads to the underutilisation of scarce spectrum resources. In addition, FSA creates a false notion of spectral scarcity. This underutilisation arises because FSA does not support spectrum handoff between TWNs, CEOs or TRAOs.

The increasing spectrum demand in TWNs, earth observations and TRAOs have motivated the design of a new spectrum allocation framework. This has necessitated the consideration of new paradigms for spectrum allocation. In [3], Haykin *et al.* present a new perspective on the application of CRs. The perspective in [3] advances [1-2] by recognising that the CR is suitable for the design of a future spectrum-allocation model. Haykin *et al.* [3] present the future spectrum-allocation model based on the supply-chain perspective. The discussion in [3] considers the legacy and cognitive TWNs, but not CEOs and TRAOs. Hence, a joint consideration of TWNs, CEOs and TRAOs is required in a future spectrum-allocation model.

The CR can be used to achieve reduced interference spectrum access between emerging technologies. The desired co-existence can be achieved using different spectrum sharing models. The feasibility of using the different CR spectrum sharing models to achieve the desired co-existence is shown in Table 2-4. Table 2-4 shows the strengths and challenges of existing co-existence and spectrum-sharing models. The CRP has been considered most for TWNs. However, the consideration for TRAOs in [13] only uses the underlying spectrum-sharing model. Furthermore, earth observation-TWN co-existence has considered the use of the CR to realise DSA between TWN subscribers and ground stations. Therefore, further work is required to ensure that the co-existence of TWNs, CEOs and TRAOs has low interference while improving spectrum utilisation.

Table 2-4: The feasibility of applying spectrum-sharing models to application pairs.

	Cognitive Radio Spectrum Sharing Model	
	Underlay	**Interweave**
ISLs-TRAOs [12;33]	The use of the underlay model requires a reduction of the satellite and satellite phones transmit power. This limits ISL throughput.	ISLs transmit; while TRAOs are not ongoing. The interweave model is feasible for ISLs when satellite ground stations are located far from the TRQZ.
TWNs-TRAOs [13; 34; 36-37].	The underlying model is unsuitable for designing interference reduction schemes between TWNs and TRAOs. Reducing TWN transmit power to achieve co-existence with TRAOs reduces subscriber throughput.	The use of the interweave model to realise low interference co-existence between TWN and TRAO requires the exchange of spectrum usage information between the TWN. This exchange should not increase computational load
TWNs-CEOs [63-64]	The spectrum underlying model can be used to achieve CEOxistence between TWNs and ground stations at the expense of reduced SINR and throughput.	The use of the interweave model in achieving co-existence between TWNs and ground stations is realizable without reducing TWN or ground station transmitting power.

The interaction between TWNs, CEOs and TRAOs in a new joint spectrum-allocation framework is shown in Figure 2-10. The framework shown in Figure 2-10 aims to reduce interference while improving spectrum utilisation and user performance. In Figure 2-10, TWNs, CEOs and TRAOs interact together in realising their spectrum access objectives. The spectrum allocation framework in Figure 2-10 comprises three non-intersecting and intersecting regions. The non-intersecting regions are regions A, B and C. Regions A, B and C describe the spectrum-access objectives of TWNs, TRAOs and CEOs, respectively. In Figure 2-10, regions AB, AC and BC arise due to the interaction between TWNs, TRAOs and CEOs. If additional spectrum is required by a technology, another technology's idle spectrum can be used to meet the demand. The re-use of unused spectral resources enhances spectrum utilisation; and considers the increasing spectrum demand of other technologies. Solutions in regions A, B or C enhance spectrum utilisation and user performance in TWNs, TRAOs and CEO, respectively.

The enhancement of spectrum-utilisation can be achieved by reducing the spectral resources used for overhead. Shared access can occur when the spectral resources allocated to another technology are idle. The re-use of idle spectral resources ensures that the requesting technology is not assigned new spectral resources.

The spectral resources that could have been assigned to the requesting technology are left for future allocation to new technologies. The spectral re-use enables sustainable spectrum allocation; because it considers the future spectrum demands of emerging technologies.

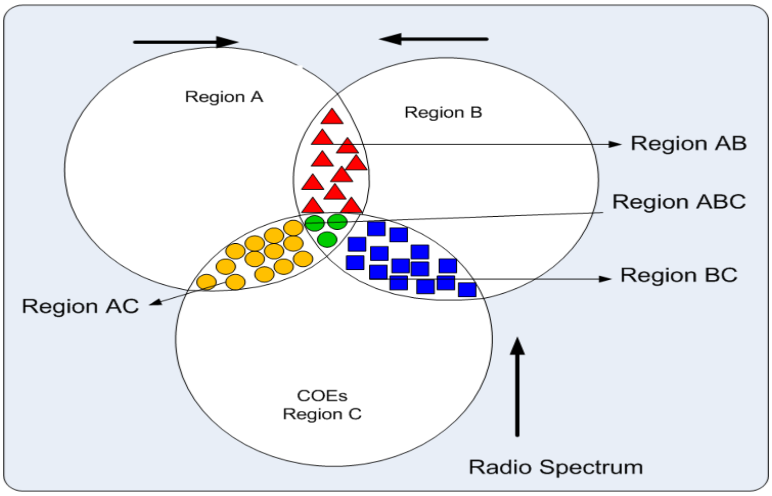

Figure 2-10: Unified architecture for spectrum access.

The spectrum-access conflicts are addressed in regions AB, AC and BC, respectively. Region AB describes the spectrum-access conflicts that arise between TWNs and TRAOs. The interference in AB is due to the presence of TWN's presence in locations that were previously considered as suitable TRQZs. The interference in BC is due to the use of ISLs in proliferating small satellites [6] and GBTs.

Region AC focuses on the spectrum-access conflicts between TWNs and CEOs. In this case, the interference arises between TWNs and the ground segment of CEOs' networks. The region ABC signifies synergies that can be formed between TWNs, CEOs and TRAOs. These synergies enhance TWNs, CEOs and TRAOs. Being reconfigurable, the CR can be used to design mechanisms that enable service interaction. This thesis is of the view that a joint consideration would enable the design of mechanisms that improve user performance in TWNs, CEOs or TRAOs.

2.7 Chapter Summary

The review shows that significant advances have been made in TWNs, earth-observation systems and TRAOs. It can be seen that TWNs have evolved because of the design of CRs, DSA and bio-inspired mechanisms. CRs have been mostly applied in TWNs with a lesser consideration in TRAOs [13] and satellite communications [65]. DSA has also been identified to be capable of enabling spectrum-sharing between earth observation and TWNs [68]. The conduct of earth-observation missions has been transformed with the advent of CEOs because of small satellite proliferation. There is also an increasing interest in conducting TRAOs. The spectrum allocation for CEOs, TWNs and TRAOs has been previously conducted separately. It is recognised in [1] that interactions between TWNs, CEOs and RAOs are necessary because of the increasing spectrum demand. Mechanisms that improve interactions between multiple technologies desiring spectrum access are also being sought in 5G wireless networks [81].

The CR can be used to reduce interference between TWNs, CEOs and TRAOs and enhance the QoS of their users. In the TWN, CRs that use ML-FNNs for spectrum prediction have a high overhead, because of training sample acquisition and ML-FNN re-training. This acquisition disregards the occurrence of similarity in the spectrum-usage pattern in the CR. The non-consideration of similarity causes CRs to re-train the ML-FNN. CRs should also be capable of transmitting as SUs in HWNs. Learning mechanisms, such as the ML-FNN can also be used for spectrum prediction by the CR in the HWN. In an HWN, CR training data acquisition can be unsuccessful due to control-channel impairments. This prevents the SU from achieving its learning objectives. The learning challenge requires the design of new mechanisms for the CR in the HWN.

In addition, TRQZs have been assumed to be capable of reducing interfererence experienced by TRAOs. However, TRQZs do not reduce TRAO-ISL interference. ISLs pose an interference threat because of the increasing proliferation of small satellite applications. Astronomical organisations can also benefit from sharing their HPCs with other technologies. Hence, a synergy benefits TWNs, CEOs and TRAOs. The CR can also be used to improve CEOs by ensuring that ground stations can access additional bandwidth. The additional bandwidth access enables MGSs to enhance their throughput while reducing interference with TWNs. Novel spectrum-access mechanisms are required to address this challenge. The incorporation of CRs can also help to improve the robustness of the CEO’s space segment.

Chapter 3

Mechanism for Enhancing Cognitive Radio QoS in TWNs

This chapter proposes a dual mode mechanism that aims to improve the CR QoS in TWNs. The proposed mechanism operates in two modes. These are the homogeneous mode and the heterogeneous mode. The homogeneous mode is activated when the CR can detect only one RAT. The heterogeneous mode is activated when the CR can detect multiple RATs. The chapter is divided into six sections. The first section discusses related work. The second describes the addressed problems. The third focuses on the motivation for using bio-inspired mechanisms. The fourth presents the proposed mechanisms. The fifth discusses simulation results. The sixth is the conclusion. The parameters used in this chapter are presented in Table 3-1.

Table 3- 1: List of parameters used in this chapter

L	Set of radio access technologies (RATs).
L_U	The U^{th} RAT
$\beta_L^i(t)$	Spectrum usage parameter matrix comprising i parameters for L at instant t.
$C(\beta_{L_U}^1(t)$	Cardinality of $\beta_{L_U}^i(t)$
$p_{L_1}(t_z)$	CR probability distributions formed from β_{L_1} at instant t_z ; $t_z \in t$.
$\kappa_L^{i'}(t)$	CR configuration parameters comprising i' parameters in L
$W_L(t)$	Set of CR's artificial neural network (ANN) weight matrices for L
i_L	CR Similarity Indicator in L
$I_{L_f}^{L_e} \in \{0,1\}$	Parameter similarity indicator between RATs L_e and L_f ; $(L_e, L_f \in L)$
z_L	CR training parameter acquisition indicator in L.
$F(W_L(t))$	Status of $W_L(t)$.
L_{CR}	CR Location
C_{ind}	Index of channel in L.
C_{sel}	Selected channel in L.
C_τ^{PU}	Primary user duty cycle in channels in L
C_{st}	State of channels in L
T_{con}	Allowable connection duration of the CR-SU on a channel in L
T_{act}	Actual connection duration of the CR-SU on a channel in L
δ	Similarity threshold for determining similarity between CR training parameters
S_M	Channel Slot Duration.
S_L	MGL
C	Set of TWN Channels.
$B_{b'}$	Bandwidth of channel $c_{b'}$; $c_{b'} \in C$ in MHz
$h_{b'}^t$	CR's Transmit gain on $c_{b'}$
$P_{b'}^t$	CR's Transmit power on $c_{b'}$
$h_{b'}^{in}$	Transmit gain of interfering neighbour on $c_{b'}$
$P_{b'}^{in}$	Transmit power of interfering neighbour on $c_{b'}'$
σ^2	Additive white Gaussian noise (AWGN)
ΔS_I	Increase in MGL due to the acquisition of training experience from more neighbouring CRs.
τ_1	Transmit duration per channel in a single mode CR that uses proposed mechanism.
γ	MGL reduction in single mode CR using proposed mechanism (homogeneous mode) in L.
τ_2	Transmit duration per channel in dual mode CR with proposed mechanism (homogeneous mode).
ζ	Delay arising due to non-ideal concurrency in dual mode CR.
τ_3	Transmit duration per channel in dual mode CR with proposed mechanism (heterogeneous mode).
$\breve{\alpha}$	Fraction of MGL spent by CR to verify predicted outputs in proposed mechanism (heterogeneous mode)
$\ddot{\upsilon}$	Missing parameter acquisition duration from CR neighbouring database in proposed mechanism.
$P_{md}^{b'}$	CR misdetection probability when verifying ANN predicted results for b'
PLR_1	Packet Loss Rate of CR using proposed mechanism (heterogeneous mode).
$P\left(\beta_L^i(t)\right)$	Probability that the CR correctly predicts $\beta_L^i(t)$ for L.

3.1 Related Work- CR in TWNs & HWNs

The use of the CR has been found to be suitable for enhancing spectrum utilisation and the QoS of TWN subscribers. Winston *et al.* [49] propose a mechanism that enables GSM mobile subscribers to utilise unused TV broadcast spectrum. The proposed mechanism uses an ANN to predict the state of TV channels. The TV broadcast technology is the PU while the cognitive radio network is the SU. The proposed mechanism improves the TWN performance by enabling the admission of more users into the network. However, it does not address the notion of false spectrum scarcity in the TWN. In addition, the mechanism does not focus on emerging TWNs such as the LTE-A which demand more spectrum.

Hei *et al.* [82] present a CR mechanism that improves LTE-A spectrum utilisation. The proposed mechanism enables the utilisation of unused spectrum via learning. The learning uses information collected by LTE-A network subscribers. The mechanism also comprises a reconfigurable radio management system located in the LTE-A core network. The management system is expected to improve the subscriber QoS and LTE-A load balancing. The proposed mechanism is of the perspective that the incorporation of the CR in LTE-A can enable network reconfiguration in LTE-A protocol stack.

Deaton *et al.* [83] extend [82] by examining the feasibility of using DSA to reducing interference in an HWN. The HWN RATs are LTE-A and GSM. The proposed framework in [83] enables the LTE-A to access more spectrum to meet subscriber demand for high throughput. The LTE-A makes opportunistic use of unutilised, TV and GSM spectrum. The channel assignment and opportunistic channel access problem is formulated as a multi-objective optimisation problem. The proposed mechanism assumes an efficient utilisation of LTE-A spectrum. This is because LTE-A is seeking to use GSM spectrum. Though the mechanism enables LTE-A to access additional spectrum and enhances GSM spectrum utilisation; it assumes full utilisation of LTE-A spectrum. The approach of multi-objective optimisation is used for the channel access problem. This technique is a non-cognitive mechanism and uses pre-defined policies written as constraints into the optimisation problem. The use of pre-defined policies can result in non-optimal decisions when unexpected network contexts are perceived by the user. Learning algorithms are cognitive and are able to improve user QoS in such cases. This drawback of non-cognitive algorithms is noted by Rakovic *et al.* [54].

Osa *et al.* [84] advance Deaton *et al.* [83] by proposing the incorporation of DSA in LTE-A. The discussion in [84] proposes the incorporation of spectrum sensing in LTE-A. In addition, the potential to incorporate DSA and CR capability in the LTE-A channel is presented. Osa *et al.* [84] also present the gap pattern parameters as being suitable for accommodating spectrum sensing in LTE-A. Furthermore, [84] advances [83] and [82] by considering the incorporation of DSA in LTE-A. Though, [84] incorporates DSA in LTE-A; additional consideration is needed to incorporate learning as proposed in [82]. Learning enables the CR to reduce interference and improve QoS in scenarios for which mathematical models are not available.

Abbas *et al.* [27] recognise that the incorporation of CRs in TWNs requires learning techniques. The learning techniques enables the CR to interactively learn from the environment thereby extending [84]. However, the discussion here focuses on the capability of different learning mechanisms suitable for CRs. Hence, additional consideration is required to investigate how incorporating learning mechanisms in TWN users can enhance spectrum utilisation in TWNs like the LTE-A.

The usefulness of learning mechanisms has been recognised as seen in [28-29, 47]. The discussion in [47] recognises that the use of learning mechanisms enhance spectrum utilisation by reducing signalling overhead. Overhead reduction makes more spectral resources available for data transmission thereby improving subscriber accessible bandwidth and QoS. These benefits can be derived in LTE-A subscribers that make use of CR spectrum prediction mechanisms.

Shahid *et al.* [48] present the channel state and idle time mechanism (CSIT). The LTE-A subscriber using CSIT has a well-trained ML-FNN. The ML-FNN enables the subscriber to predict future channel state and connection duration. CSIT makes use of the LTE-A channel structure for its training data acquisition and spectrum prediction. The subscriber re-acquires the training data at pre-determined epochs to ensure that the learning is updated. The re-training assumes that there are no similarities in LTE-A spectrum usage. CSIT can be extended by presenting a mechanism to detect the presence or absence of similarities. The CR QoS can be enhanced if the subscriber can detect similarities because re-training is not executed at such epochs. During these epochs, subscriber QoS can be enhanced since spectral resources allocated to re-training and re-acquisition are used for data transmission.

CRs are also expected to be capable of transmitting in HWNs; HWNs are a more complex environment than single radio access technology (RAT) wireless network environment. In the HWN, the CR is expected to learn with the aim of executing RAT selection. The discussion in [83] demonstrates the potential of CRs to enhance spectrum utilisation. However, [83] does not consider RAT selection. Learning mechanisms such as ANNs can be used to design cognitive RAT selection mechanisms [54]. Cognitive RAT selection mechanisms have been recognised to be more suitable than non-cognitive selection mechanisms [54].

In addition, the role of learning mechanisms has been demonstrated for RAT selection in [50]. Tsakgaris *et al.* [50] propose an SOM-NN that selects between IEEE 802.11b and IEEE 802.11g using the predicted bit rate. The discussion in [50] demonstrates that CR ANNs can learn with the aim of reducing interference and subscriber QoS. The scenario in [60] advances [50] by considering selection between RATs using unlicensed spectrum (IEEE 802.11) and licensed spectrum (3G). The scenario presented in [50] considers only RATs using unlicensed spectrum.

Rao *et al.* [55] present the always best connected and served paradigm for RAT selection in HWNs. The paradigm recognises the suitability of learning mechanisms for the RAT selection process in next generation wireless networks. The transmission of CRs in HWNs should also ensure that spectrum utilisation is enhanced.

The role of spectrum prediction has largely being considered for CRs in TWNs. The CR operating as an SU in the HWN should select the best RAT and its most suitable channel. The learning objective should incorporate channel access parameters in the HWN RATs. However, this is not considered in existing work.

Furthermore, the use of learning mechanisms has been widely recognised as beneficial to CRs. Learning mechanisms such as the ANN are implemented as software entities on the CR. Being implemented as software on the CR, the ANN is susceptible to CR operating system software faults. The faults prevent the CR from using the ANN for spectrum prediction when required.

3.2 Problem Description

The scenario being considered comprises PUs, and CRs, i.e. SUs in an HWN. The HWN comprises infrastructure based RATs. The central infrastructure, PUs and CRs have the following capabilities:

1) **Central Infrastructure :** The central infrastructure co-ordinates communications between RAT users and transmits training information to incoming CRs via the control channel. It computes and is aware of previous throughput on RAT channels and allowable channel-connection duration.
2) **Primary users (PUs):** The primary users have a higher spectrum access priority than CRs i.e. SUs. They can access licensed spectrum. PUs do not compete with other PUs.
3) **Cognitive radios (CRs):** CRs are SUs and access the licensed spectrum of RATs when the PUs of the RATs are absent. They are equipped with a well-trained ANN for both RATs. The RATs being considered have defined gap and data transmit slots. The CR acquires the training data during the measurement gap slots; and transmit data during the data transmit slots. There are two types of CR in the TWN. These are the incoming CR and the existing CR. The existing CR have engaged in data transmission in the RAT serving as the current point of attachment. They transmit their experience i.e. acquired training data to the incoming CR. Incoming CRs acquire training data from the existing CRs. CR transmission upholds the CPP. The incoming CR forms distributions from the training data being accessed. The incoming and existing CRs have reprogrammable RAT specific ANNs. The ANN is designed using a reprogrammable computing architecture such as the field programmable gate array. The field programmable gate array can be reprogrammed and useful in designing adaptive systems [85]. The ANN architecture is reprogrammed by changing the number of layers or number of neurons per layer or layer transfer functions. ANN reprogramming aims to improve spectrum prediction accuracy.

The incoming CR is considered to have the following time-varying parameters:

1) The spectrum usage-parameter matrix, $\left(\beta_L^i(t)\right)$ for infrastructure based RATs. The set of RATs, L is $L = \{L_1, L_2, \dots, L_U\}$. The spectrum usage parameter matrix $\left(\beta_L^i(t)\right)$ comprises channel related parameters. Examples of parameters in $\left(\beta_L^i(t)\right)$ are the channel idle state and allowable channel

transmit duration. These parameters are held in $\left(\beta_L^i(t)\right)$'s indexes. The incoming CR acquires $\left(\beta_L^i(t)\right)$ from existing CRs.

$$\beta_L^i(t) = \begin{pmatrix} \beta_{L_1}^1(t), & \beta_{L_2}^1(t), & \dots & ,\beta_{L_U}^1(t) \\ \beta_{L_1}^2(t), & \beta_{L_2}^2(t), & \dots & ,\beta_{L_U}^2(t) \\ \vdots & \vdots & \vdots & \vdots \\ \beta_{L_1}^m(t), & \beta_{L_2}^m(t), & \dots & ,\beta_{L_U}^m(t) \end{pmatrix}; t = \{t_1, \dots, t_a\} \tag{3.1}$$

Where i; $i = \{1, \dots, m\}$ is the set of spectrum usage parameters.

2) CR distributions $p_L(t)$, formed from $\beta_L^i(t)$.

$$p_L(t) \;=\; (p_{L_1}(t), p_{L_2}(t), \dots, p_{L_U}(t))\,; t = \{t_1, \dots, t_a\} \tag{3.2}$$

3) ANN weights matrix, $W_{L_e}(t)$ for L_e's ANN; $(L_e \epsilon\, L)$. The weight matrix $W_{L_e}(t)\,;\ t = \{t_1, \dots, t_a\}$ comprises the CR ANN's input, hidden and output-layer weights. The ANN is described by its weights. In the RAT L_e, the CR derives $W_{L_e}(t)$ by using $\beta_{L_e}^i(t)$ for training.

$$W_{L_e}(t) = \left(W_{input}^{L_e}(t), W_{hidden}^{L_e}(t), W_{output}^{L_e}(t)\right) \tag{3.3}$$

Where $W_{input}^{L_e}(t)$, $W_{hidden}^{L_e}(t)$ and $W_{output}^{L_e}(t)$ are the input, hidden and output layer weights of L_e's ANN at instant t, respectively.

Let $i_{L_e} \epsilon \{0,1\}$ be the CR similarity indicator in L_e. The values $i_{L_e} = 0$ and $i_{L_e} = 1$ signify that $p_{L_e}(t_z)\,;\ \left((t_z)\ \epsilon\ t\right)$ and $p_{L_e}(t_{z-1})\,;\ \left((t_{z-1})\ \epsilon\ t\right)$, are dissimilar and similar, respectively. In L_e, the CR needs to re-train its ANN when, $i_{L_e} = 0$. The CR does not need to re-train its ANN in L_e when $i_{L_e} = 1$. However, the CR in L_e needs to be capable of detecting when $i_{L_e} = 1$. The first objective addressed in this chapter is enabling the CR to detect when $i_{L_e} = 1$.

In addition, let $I_{L_f}^{L_e}\ \epsilon\ \{0,1\}$; $\left(L_f \in L\ \right)$ be the CR parameter similarity indicator for RATs L_e and L_f. The values $I_{L_f}^{L_e} = 0$ and $I_{L_f}^{L_e} = 1$ signify that some spectrum usage parameters of L_e and L_f are not closely and closely related, respectively. Let $z_{L_e}\ \epsilon\ \{0,1\}$ be the training parameter acquisition indicator in L_e. The values, $z_{L_e} = 0$ and $z_{L_e} = 1$, signify incomplete and complete acquisition of $\beta_{L_e}^i(t)$ in L_e, respectively.

Furthermore, let $F\left(W_{L_e}(t)\right) \epsilon \{0,1\}$ be the status of $W_{L_e}(t)$ at instant t. The value $F\left(W_{L_e}(t)\right) = 0$ signifies that L_e's ANN is non-functional due to reprogramming failure in the field programmable gate array. The value $F\left(W_{L_e}(t)\right) = 1$ signifies that L_e's ANN is functional i.e. reprogramming is successful. In an HWN comprising L_e and L_f the CR is unable to achieve learning when $\left(z_{L_e} = 0\,;\ z_{L_f} = 1\,, I_{L_f}^{L_e} = 1\right)$. The CR in an HWN comprising L_e and L_f cannot achieve spectrum prediction when $\left(F\left(W_{L_e}(t)\right) = 0\right)$. The second objective addressed in this chapter is enabling the CR in an HWN to overcome this challenge.

3.3 Motivation For Using Bio-Inspired Mechanisms

This section presents the motivation for using bio-inspired mechanisms to address the identified CR problems. It is divided into two parts. The first and second part presents the immune system and cell transcription mechanisms, respectively.

3.3.1 Motivation for using the Immune System

The immune system generates a suitable response to fight pathogens; and it comprises the innate and adaptive immune subsystems [86]. It also comprises self and non-self-cells. The innate immune subsystem is trained initially to identify self- and non-self-cells. Self-cells are native to the human system; while non-self-cells arise from the external environment. The innate immune subsystem identifies self-cells and non-self-cells. It classifies a cell as either self- or non-self; and it determines an appropriate response to fight non-self-cells. No self-cell identification is performed by using the information obtained from antigen-presenting cells. The adaptive immune subsystem differs from the innate immune subsystem; because it is continuously being trained to combat pathogens.

Previously, the innate immune subsystem was regarded as static. However, Quintin *et al.* [87] note that the innate immune subsystem also has a dynamic component. The innate immune subsystem uses memory cells for the self- and non-self-cell identification via cell comparisons.

The immune system forms a distribution by using previous pathogen information obtained from antigen-presenting cells. The information obtained from antigen presenting cells is compared with the previous memory cell contents, to determine the system's response. The comparison improves the pathogen-combating capability; because the immune system begins combating the invaders prior to a total pathogen invasion. The immune system compares antigen presenting information. This comparison enables the CR to determine when acquired distributions are similar.

3.3.2 Motivation for using Cell Transcription

The cell transcription mechanism enables cell-reprogramming and is described in [85]. The cell re-programming is achieved by DNA transcription. The generation of DNA transcripts is achieved by selectively copying some components from a DNA. The generated transcript can be used at a later time to re-program another DNA. The re-programmed DNA has the capability of the DNA from which the transcript was initially generated.

In addition, transcription enables the biological cellular system to have a robust behaviour. The developed robust behaviour can be further used to enhance neural network systems. According to Balaban *et al.* [88], neural networks have a contributory effect on each other. The outputs of a neural network can serve as the inputs to another neural network. The contributory effect has been observed to improve the robustness of biological neural networks [88]. The ability of the neural network to use inputs from other neural networks is called input source heterogeneity (ISH). ISH can be used to realise CR learning in an HWN comprising L_e and L_f when $z_{L_e} = 0$ if $z_{L_f} = 1$, $I_{L_f}^{L_e} = 1$. Transcription can be used to realise spectrum prediction in a RAT when the field programmable gate array of its ANN experiences re-programming failure.

3.4 Proposed Mechanism

This section presents the proposed mechanism. The proposed mechanism operates in two modes. The first mode is the homogeneous mode. In this mode, the CR detects one RAT. The second mode is the heterogeneous mode when the CR is in an HWN. This section is divided into two parts. The first and second part describes the proposed mechanism and formulates the performance model, respectively.

3.4.1 Homogeneous and Heterogeneous Mode

The CR using the proposed mechanism has a reconfigurable ANN. The reconfigurable ANN is trained using different parameters in the heterogeneous and homogeneous mode. In the homogeneous mode, the CR is concerned with transmitting in the RAT while upholding the CPP. The CR parameters are the channel state, allowable connection duration occupancy status, resource block and idle time slots. These are the training parameters used in CSIT [48]. In the homogeneous mode, the CR uses the same ANN as [48].

In the heterogeneous mode, the CR's RAT specific ANN is a cascade feedforward neural network (CC-FNN). The CR aims to learn and select the best RAT and channel that upholds the CPP. The CR has multiple RAT-specific CC-FNNs. Each CC-FNN has own database that holds RAT specific training parameters. The RAT specific CC-FNNs interact and exchange similar training parameters from their databases with each other. The training parameters are the CR location (L_{CR}), RAT channel-specific index (C_{ind}) and PU channel-specific duty cycle (C_τ^{PU}), selected channel (C_{sel}), RAT channel-specific state (C_{st}), channel specific allowable connection duration (T_{con}) and RAT index. It is self-aware and can determine (L_{CR}). The RAT index and L_{CR} are used to determine C_{sel}, C_{st}, C_τ^{PU} and T_{con} via a trained ANN. The CR determines the C_{sel} and C_{ind} that upholds the CPP at L_{CR}. The CR's ANN architecture in the heterogeneous mode is shown in Figure 3-1. The CR's actual connection duration on a RAT channel, T_{act} is determined as:

$$T_{act} = T_{con} \times C_\tau^{PU} \tag{3.4}$$

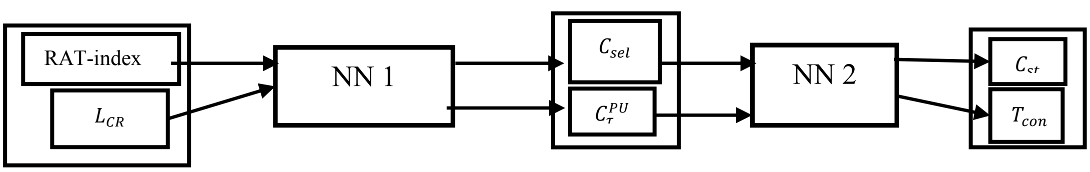

Figure 3-1: ANN architecture in heterogeneous mode.

The heterogeneous mode ANN architecture is a combination of two ANNs and not a single ANN. This is because of the logical relations between the predicted parameters. The selected channel and PU duty cycle are outputs that are dependent on the channel in a given RAT at a CR location. The channel state and allowable connection duration are determined for a given channel considering the PU channel duty cycle.

The CR switches between the ANN used in CSIT and the architecture in Figure 3-1. The heterogeneous mode ANN is trained when the TWN subscriber is not engaged in data transmission. The mechanism's flowchart is presented in Figure 3-2.

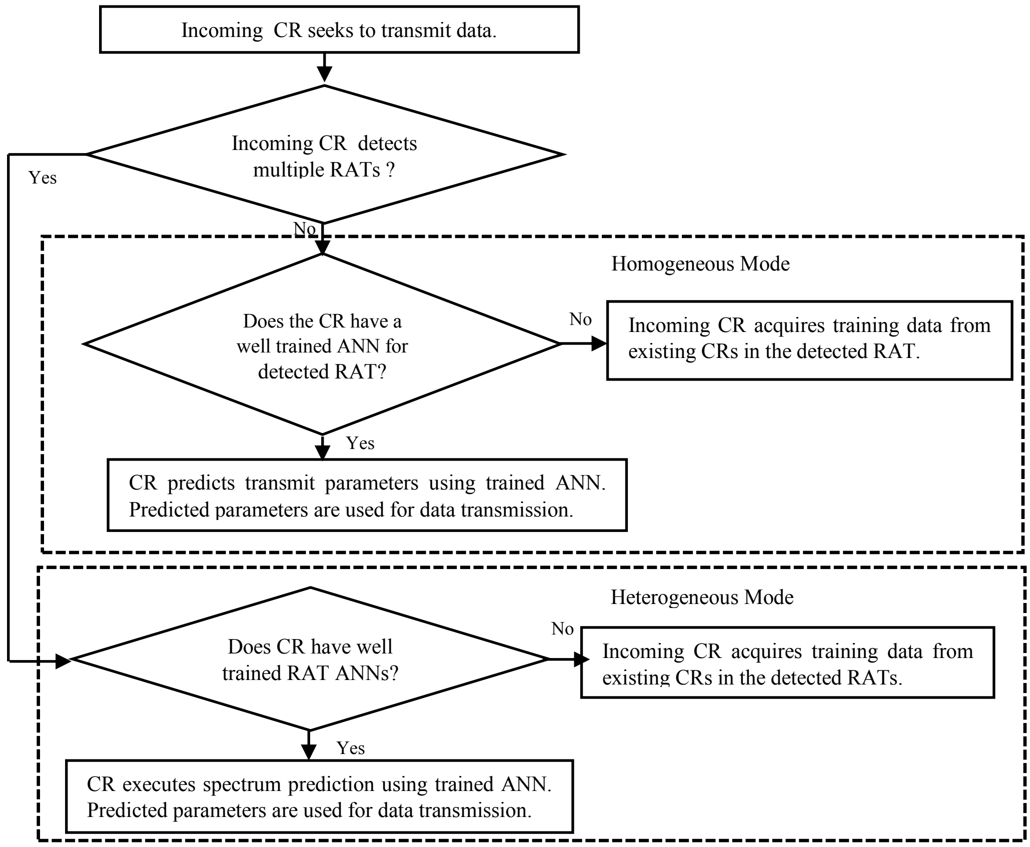

Figure 3-2: ANN architecture switching for CR in homogeneous and heterogeneous modes.

The CR incorporating the proposed mechanism (homogeneous mode) aims to prevent ANN retraining in L_e when $i_{L_e} = 1$. In CSIT [48], the data acquisition does not consider similarities in the spectrum usage matrix. Therefore, CR ML-FNNs are retrained – when there are similarities between previously and recently acquired training parameters. The consideration of similarities can reduce the measurement gap duration and increase the CR data transmit duration. However, CRs using CSIT miss the opportunity that could be used to improve their data transmit duration and throughput. The opportunities arise when similarities occur.

The cognitive cycle enables CRs to sense the network, make inferences by using the sensed information, and execute reconfiguration decisions. Incorporating ML-FNN adds training and output prediction stages, resulting in the CR learning cycle. CRs incorporating ML-FNNs need to acquire training data prior to ML-FNN training and spectrum prediction. The CR in L_e can reduce the battery power expended on ANN re-training when $i_{L_e} = 1$.

The TWN state perceived by CR during spectrum sensing can be considered to comprise known and unknown mobile network states. Changes in the network state arise due to transitions between different mobile network-environment states. A TWN environment state can be either a quasi-mobile network state or an unknown mobile network state. A quasi-mobile network state is one in which the TWN state seems to have changed significantly. The CR has two transition paths. The first path is between known quasi-mobile environment states. The second is between unknown radio environment states.

The incorporation of the ANN spectrum prediction in CRs in [48] considers the second transition path and not the first path. Therefore, CRs using the mechanism in [48] bear the full costs of ML-FNN training and prediction in the first and second paths. In the first transition path, the CR is aware of the starting and the destination network states. These states are quasi-mobile states. The CR has acquired awareness of these states from previous epochs. CRs are aware of the states lying between the quasi-mobile states.

The state scenario as perceived by the CR in the homogeneous mode is shown in Figure 3-3. Figure 3-3 shows the transition between quasi-mobile radio network states A and B and the unknown mobile network state A. There are four states on path A between quasi-mobile network states A and B. Similarly, there are four states on path B between quasi-mobile network state A and the unknown mobile network state B.

The CR should be able to switch between the paths A and B. Training data re-acquisition is not necessary for CRs using ML-FNN for spectrum prediction on path A. In path A, the CR can re-use the previously computed ML-FNN weights. The re-use of ML-FNN weights reduces the portion of the measurement gap length (MGL) used for ML-FNN training. The MGL reduction improves the DTT and CR throughput. However, CRs require a new model that considers paths A and B. This model is proposed in this chapter using immune system concepts.

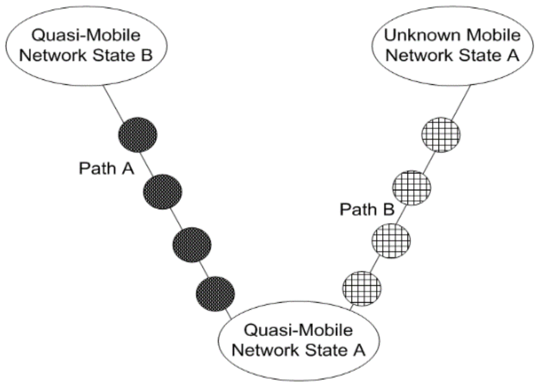

Figure 3-3: Mobile network state transitions for cognitive radios.

The immune system can be used to design a model for CRs. In this model, immune memory cells correspond to the CR memory. The incorporation of concepts from the immune system enables CRs to classify information as self or non-self-cells. Self and non-self cells correspond to similar and dissimilar CR distributions, respectively. In CSIT [48], CRs acquire information from other CRs without classifying them as self or non-self-cells. However, when CRs have self-cells, complete training data re-acquisition and re-training are not necessary. Existing ML-FNN weights can be re-used for spectrum prediction. Given a similarity threshold, (δ), RAT L_1's environment is quasi-mobile if:

$$\left|\left(p_{L_1}(t_z)\ log_{10}\left(\frac{p_{L_1}(t_z)}{p_{L_1}(t_{z-1})}\right)\right)\right| \leq \delta\ ;\ (t_{z-1}\ , t_z)\ \epsilon\ t \quad (3.5)$$

Equation (3.5) is the neural-similarity condition (NSC); and the value of δ is chosen to ensure that the CR upholds the CPP. When the NSC is satisfied, the CR can avoid re-acquiring training data and re-training its ML-FNN. The MGL can be reduced. For non-identical CR distributions, training data-reacquisition and ML-FNN retraining are necessary.

The proposed mechanism can be used by single and dual mode CRs. The discussion above has focused on the single mode CR. In the dual mode CR, training data acquisition and data transmission can be executed concurrently. However the discussion in [20, 31-32] has not considered the NSC for the dual mode CR. The flowchart for the mechanism (homogenous mode) when used by the single mode CR is shown on the left hand side in Figure 3-4. The flowchart for the mechanism (homogeneous mode) when used by the dual mode CR is shown on the right hand side in Figure 3-4. NSC execution enables the CR to re-use the ML-FNN weights to determine the data-transmission parameters via spectrum prediction.

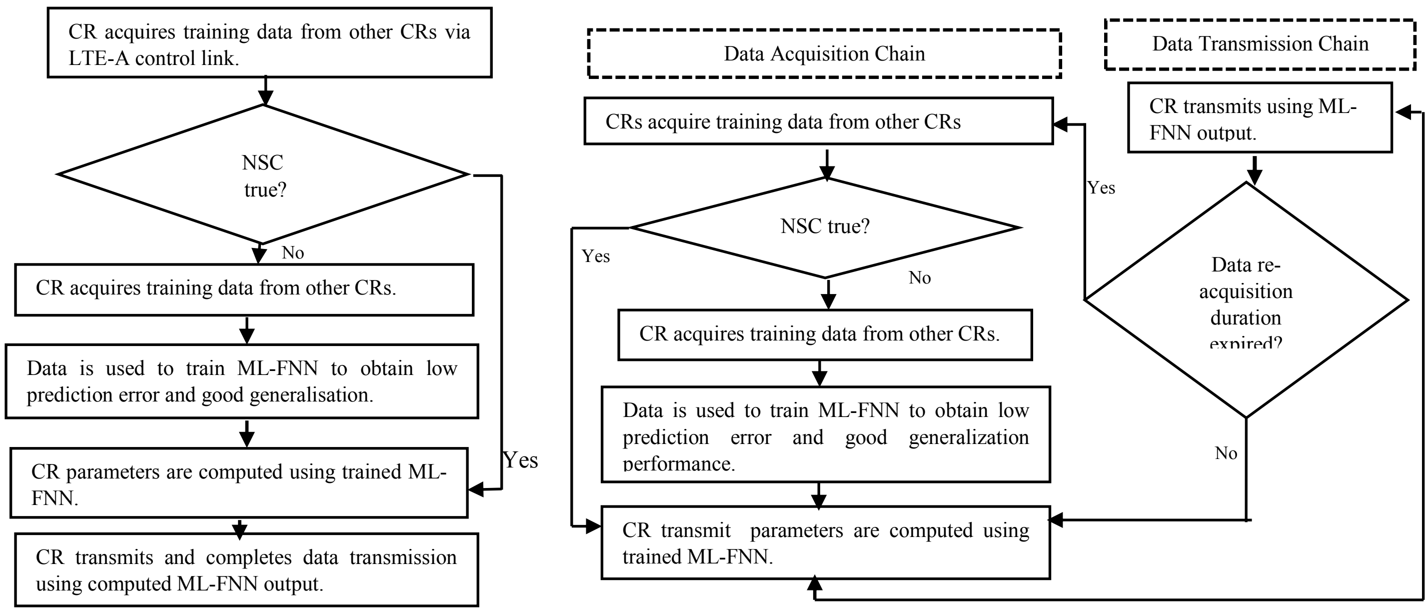

Figure 3-4: Homogenous mode: single mode CR (left) and dual mode CR (right).

The heterogeneous mode is triggered when the CR detects multiple RATs. The CR has RAT specific ANNs and seeks to transmit while upholding the CPP. The parameters $\beta^1_{L_1}(t)$ and $\beta^1_{L_2}(t)$ obtained in L_1 and L_2, respectively are similar when:

$$\frac{1}{C(\beta^1_{L_1}(t))}\left|\sum_{t=t_1}^{t_a}\left(\beta^1_{L_1}(t)-\beta^1_{L_2}(t)\right)\right| \leq \delta;\ C(\beta^1_{L_1}(t)) = C(\beta^1_{L_2}(t)) \quad (3.6)$$

Where $C(\beta^1_{L_1}(t))$ and $C(\beta^1_{L_2}(t))$ are the cardinalities of $\beta^1_{L_1}(t)$ and $\beta^1_{L_2}(t)$, respectively.

ISH enables learning when $z_{L_e} = 0$ if $z_{L_f} = 1$, $I_{L_f}^{L_e} = 1$. The transcription mechanism enables spectrum prediction in L_e when $F(W_{L_e}(t)) = 0$. The flowchart of the ISH and transcription mechanism is shown in Figure 3-5. ISH enables the sharing of similar parameters when (3.6) holds true. ISH is used to realise interactions between the CR's RAT specific databases. The interaction between RAT databases enables the CR to achieve learning in the RAT with a missing parameter. The transcription mechanism enables the execution of spectrum prediction in L_e when its ANN's field programmable gate array reprogramming fails.

In Figure 3-5, the CR has RAT specific databases and ANNs. The ANNs are trained using the training parameters acquired and stored in the RAT specific database. The developed ANN matrices are extracted and stored in a transcription layer. The stored matrices are used for spectrum prediction when reprogramming the ANN's field programmable gate array fails. The use of the matrices stored in the transcription layer enables the CR to use one RAT specific CC-FNN.

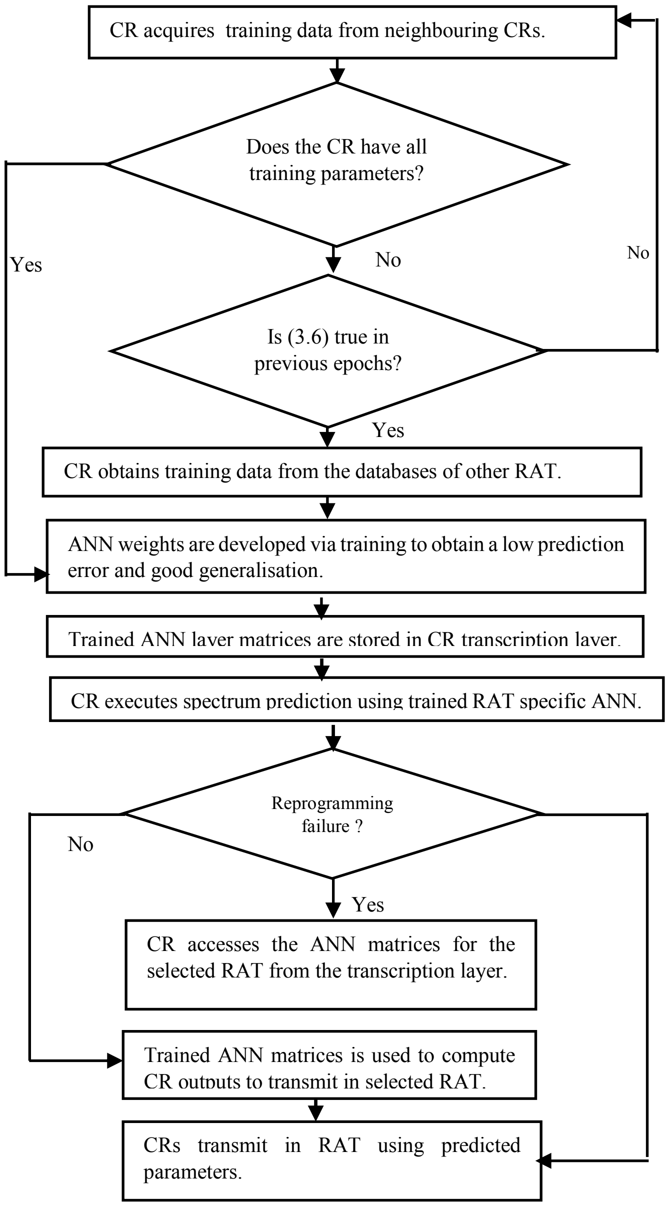

Figure 3-5: Cognitive radio mechanism in heterogeneous Mode.

3.4.2 Performance Formulation

This section formulates the performance model for the proposed mechanism. In the homogeneous mode, the CR is assumed to have a well-trained ML-FNN. The CR has been shown to have a well-trained ML-FNN. The CR metrics are the data transmit time (DTT), throughput, i.e. the amount of transmitted data and signalling overhead. The CR seeks to transmit for a longer period and send more data on a channel. The CR transmits more data by having a longer channel connection duration for a given channel capacity (in bits per seconds). Hence, the amount of data that can be sent by the CR is considered. The following parameters are used here:

Table 3- 2: List of parameters used in performance formulation.

S_M	Channel Slot Duration.
S_L	MGL
C	Set of TWN Channels.
$B_{b'}$	Bandwidth of channel $c_{b'}$; $c_{b'} \epsilon\ C$ in MHz
$h_{b'}^{t}$	CR's Transmit gain on $c_{b'}$
$P_{b'}^{t}$	CR's Transmit power on $c_{b'}$
$h_{b'}^{in}$	Transmit gain of interfering neighbour on $c_{b'}$
$P_{b'}^{in}$	Transmit power of interfering neighbour on $c_{b'}{}'$
σ^2	Additive white Gaussian noise (AWGN)
ΔS_I	Increase in MGL due to the acquisition of training experience from more neighbouring CRs.
τ_1	Transmit duration per channel in a single mode CR that uses proposed mechanism.
γ	MGL reduction in single mode CR using proposed mechanism (homogeneous mode) in L.
τ_2	Transmit duration per channel in dual mode CR with proposed mechanism (homogeneous mode).
ζ	Delay arising due to non-ideal concurrency in dual mode CR.
τ_3	Transmit duration per channel in dual mode CR with proposed mechanism (heterogeneous mode).
ᾰ	Fraction of MGL spent by CR to verify predicted outputs in proposed mechanism (heterogeneous mode)
ΰ	Missing parameter acquisition duration from CR neighbouring database in proposed mechanism.
$P_{md}^{b'}$	CR misdetection probability when verifying ANN predicted results for b'
PLR_1	Packet Loss Rate of CR using proposed mechanism (heterogeneous mode).
$P\left(\beta_L^i(t)\right)$	Probability that the CR correctly predicts $\beta_L^i(t)$ for L.

Let C be the set of TWN channels, defined as,

$$C = \{c_1, \dots, c_b\} \tag{3.7}$$

In formulating the throughput, let the channel time slot and MGL be denoted as S_M and S_I, respectively. In addition, the CR can transmit over bonded channels. The CR channel capacity is :

$$channel\ capacity \ = \sum_{b'=1}^{b} B_{b'} \log_2\left(1 + \frac{|\ h_{b'}^{t}\ |^2 P_{b'}^{t}}{\left(|\ h_{b'}^{in}\ |^2 P_{b'}^{in}\right) + \sigma^2}\right). \tag{3.8}$$

Where

$B_{b'}$, $h_{b'}^{t}$ and $P_{b'}^{t}$ are the channel bandwidth in (Hz),CR transmit gain and power on $c_{b'}$, ($c_{b'} \epsilon\ C$), respectively. $h_{b'}^{in}$ and $P_{b'}^{in}$ are the interference channel gain and interference power experienced by CR from $c_{b'}$'s interfering neighbour, respectively.

In the homogeneous mode, the single mode CR's MGL is reduced by γ seconds. The CR DTT per channel (τ_1) is :

$$\tau_1 = \ (S_M - (S_L - \gamma)) \tag{3.9}$$

Dual-mode CRs using the proposed mechanism (homogeneous mode) concurrently executes data transmission and training data acquisition. They have a delay ζ arising between training data acquisition and data transmission due to non-ideal behaviour. The CR DTT, per channel (τ_2) is:

$$\tau_2 = S_M - (\zeta - \gamma) \,. \tag{3.10}$$

In the heterogeneous mode, the single mode CR spends a fraction, ἀ of the MGL, (S_I) to verify the predicted results. The ANN is trained during periods when user is not transmitting data. The CR transmit duration per channel, τ_3 is:

$$\tau_3 = \left(S_M - (\ddot{\alpha} S_I + \ddot{\upsilon})\right);\;\; \ddot{\alpha} < 1;\; \ddot{\upsilon} < \ddot{\alpha} S_I \tag{3.11}$$

Where ϋ is time taken to exchange similar parameters between the databases of different RATs in the CR via ISH.

The proposed mechanism aims to enable the CR transmit more data on a channel. The transmitted data in this case is given as:

$$Transmitted\ Data = \begin{cases} \tau_1 \text{x}\ channel\ capacity\,; (Single\ mode\ CR\ \ (Homogeneous\ Mode)) \\ \tau_2 \text{x}\ channel\ capacity\,; (Dual\ Mode\ CR\ \ (Homogeneous\ Mode)) \\ \tau_3 \text{x}\ channel\ capacity\,; (Single\ Mode\ \ CR\ \ (Heterogeneous\ Mode)) \end{cases} \tag{3.12}$$

The packet loss rate is formulated for the heterogeneous mode. In the homogeneous mode, the CR uses the same ANN architecture as CSIT [48]. This chapter extends CSIT by incorporating immune system concepts to consider the existence of similarities in spectrum usage. The use of immune system concepts increases the CR DTT and the amount of transmitted data.

In CRs using ANNs for spectrum prediction, the packet loss rate depends on the number of predicted parameters and correct prediction accuracy of each parameter. Since, CSIT [48] and the proposed mechanism (homogeneous mode) use the same ANN architecture, they have the same packet loss rate. However, the proposed mechanism (homogeneous mode) enhances the CR DTT, amount of data transmitted and reduces signalling overhead. The homogeneous mode is suited for enhancing the QoS of error tolerant applications.

In the heterogeneous mode, packet loss occurs when there is a misdetection event with probability, $P_{md}^{b'}$ on $c_{b'}$. Let $P\left(\beta_{L_1}^{i}(t)\right)$ be $\beta_{L_1}^{i}(t)$'s correct prediction probability in L_1 at instant t. The packet-loss rate, (PLR_1) is:

$$PLR_1 = \prod_{b'=1}^{b} P_{md}^{b'} \times \prod_{i=1}^{m} \left(1 - P\left(\beta_{L_1}^{i}(t)\right)\right) \tag{3.13}$$

3.5 Performance Evaluation

This section discusses the simulation results obtained for proposed dual mode mechanism in homogeneous and heterogeneous modes. The performance metrics for the proposed mechanism in the homogeneous mode are the CR DTT, CR throughput and the MGL reduction. The performance metrics for the proposed mechanism in the heterogeneous mode are: CR throughput, prediction accuracy, and interference reduction probability. The signalling overhead is also investigated.

The simulation environment comprises SUs with well-trained ANNs in LTE-A. These ANNs have been trained using data acquired during epochs of low CR low activity. CR communications are in the radio-resource control (RRC)-CONNECTED state, where MGL = 6ms, MGRP = 40ms. The values of MGL and MGRP have been chosen as defined in 3GPP Release 8. Single-mode and dual-mode CRs uphold the CPP.

The incorporation of the proposed mechanism (homogenous mode) reduces the MGL and improves the DTT. In computing the NSC verification execution duration, it is assumed that the number of bonded channels does not exceed that used in training the ML-FNN. This prevents a scenario, where the ANN is expected to predict for channels where no training data have been obtained. The obtained result is shown in Figure 3-6.

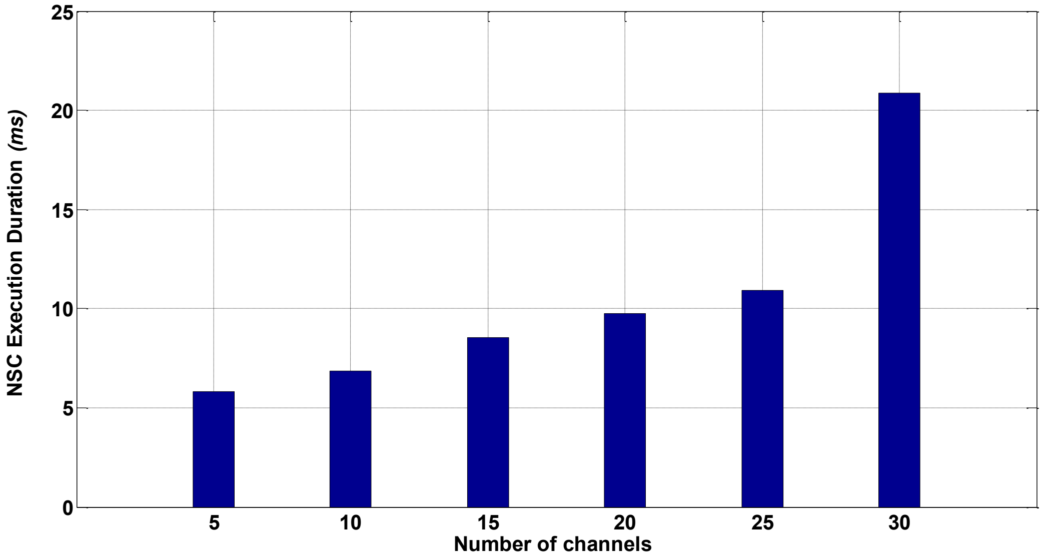

Figure 3-6: CR NSC Execution Time.

As shown in Figure 3-6, the computation duration increases with the number of channels. CRs have larger databases when ANNs have been trained for more channels. There is more time saving in reducing the MGL and increasing the DTT, when the NSC is true for more channels. The computation time is longest, when the NSC validity is investigated for 30 channels.

The CR DTT is also investigated and shown in Figure 3-7. From Figure 3-7, it can be seen that the CR-DTT is constant in CSIT. This is because the MGL is fully observed for each channel in the LTE-A RRC CONNECTED state. A higher CR DTT is observed with an increasing number of channels for single and dual mode CR in the homogeneous mode. The CR DTT increases because of the reduced MGL when more channels have similar spectrum-usage patterns.

Investigation shows that the MGL is reduced by an average of 88.8% when compared to CSIT. The MGL reduction is the same for dual-mode and single-mode CRs. The MGL is reduced by 24.2 ms, 53.1ms and 81.5ms, when CRs bond 5, 10 and 15 channels, respectively.

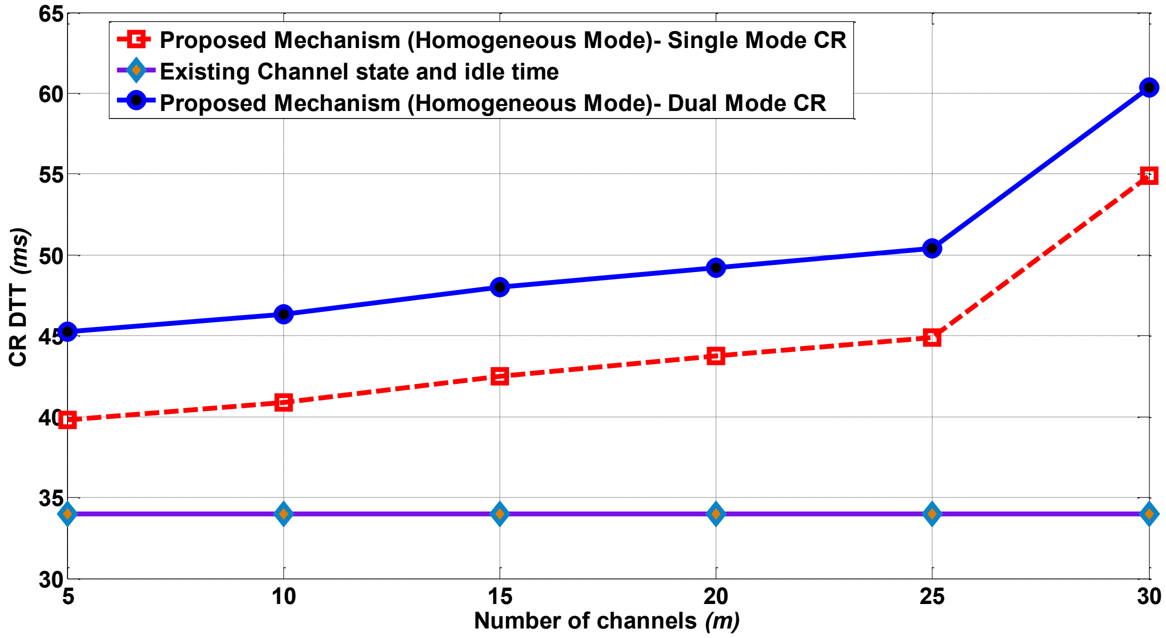

Figure 3-7: Improvement in CR DTT of the proposed mechanism in homogeneous mode.

The CR-DTT is enhanced by 30.8% on average when single-mode CRs use the proposed mechanism (homogeneous mode) compared with CSIT. The proposed mechanism (homogeneous mode) enhances the dual mode CR's DTT by 46.8%, when compared with single-mode CRs using CSIT. The dual mode CR has a higher improvement; because it can jointly execute data transmission and NSC verification. The dual mode CR's DTT exceeds the single-mode CR's DTT by 16% when both use the proposed mechanism (homogeneous mode). It can also be seen that the improvement of the CR-DTT of 30.8% and 46.8% both fall short of the MGL reduction percentage, i.e. 88.8%. The reduction is due to the spectrum-sensing requirements necessary to uphold the CPP. The CR–DTT also influences the CR throughput (in bytes) i.e. the amount of transmitted data. The throughput for CSIT (single-mode CRs), proposed mechanism (homogeneous mode) in single and dual mode CRs is investigated and shown in Figure 3-8.

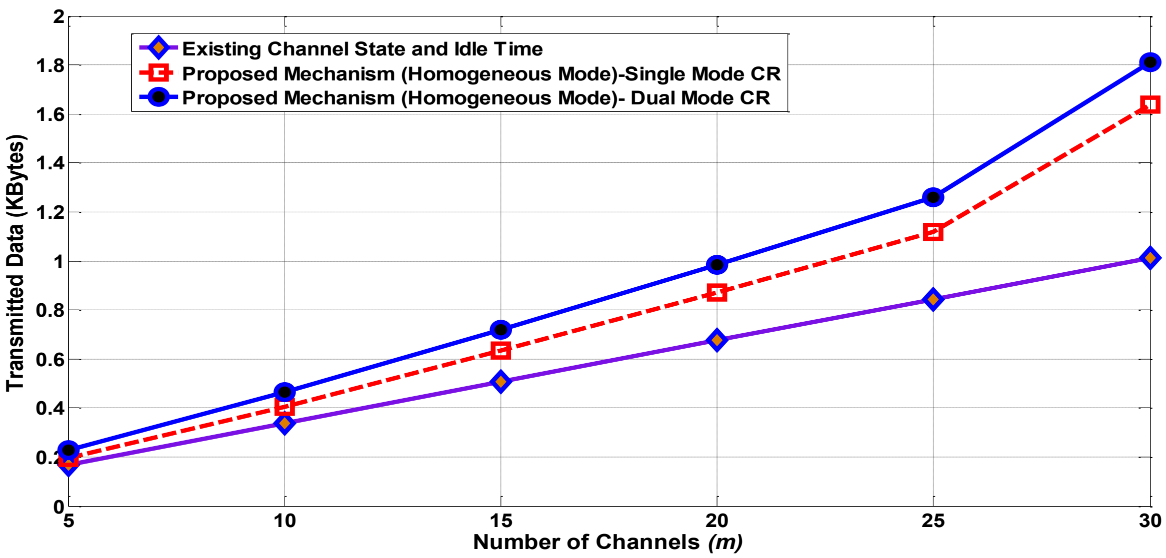

Figure 3-8: Cognitive radio channel capacity in existing and proposed mechanism (homogeneous mode)

It is observed from Figure 3-8 that CR throughput increases with the number of channels i.e. accessible bandwidth in the proposed mechanism (homogeneous mode) and CSIT. Dual-mode CRs using the proposed mechanism (homogeneous mode) have a higher throughput than single-mode CRs.

The incorporation of the proposed mechanism (homogeneous mode) in single-mode CRs enhances the throughput by an average of 31%, compared to CSIT. The existing CSIT [48] uses a single-mode CR and does not verify the NSC in LTE-A. Hence, the proposed mechanism (homogeneous mode) enhances single-mode CR throughput. This thesis also investigates how the dual mode CR enhances the throughput, when compared with the single-mode CR using CSIT. The dual-mode CR using the proposed mechanism (homogeneous mode) has a higher throughput than single-mode CR using CSIT. The throughput of the dual mode CR using the mechanism (homogeneous mode) outperforms that of CSIT by 48% on average. Hence, the concurrent capacity in the dual mode CRs enhances CR throughput by an average of 17%. The proposed mechanism (homogeneous mode) uses 0.7GB and can be used by a CR with up to 2GB RAM.

In investigating the performance of the mechanism in the heterogeneous mode, it is assumed that the CR is in an HWN comprising LTE-A and UMTS; and has selected LTE-A. In LTE-A, the CR predicts C_{st},T_{all} C_{sel} C_{τ}^{PU} and assumes that the NSC holds true during previous epochs. The ANN comprises neural blocks NN 1 and NN 2. NN 1 and NN 2 are trained using the C_{τ}^{PU}acquired from the UMTS database via ISH. A trained NN 1 can predict C_{τ}^{PU} that serves as an input to NN 2. NN 2 predicts C_{st} and T_{all}, thereby realising CR prediction.

NN 1 and NN 2 are designed and trained using the MATLAB neural network object oriented framework in MATLAB R2013a. The design parameters are shown in Table 3-3 Studies such as [16,48] show that statistical distributions can be used to describe spectrum usage parameters. The PU channel duty cycle, channel state and allowable SU connection duration are modelled using the Beta [16], Poisson [48] and Pareto distribution [48], respectively.

Table 3.3: CC-FNN design p arameter.

Parameter	Value	
	NN 1	**NN 2**
Number of Hidden Layers	**2**	**3**
Number of Inputs	**2**	**2**
Number of Outputs	**2**	**2**
Hidden Layer Configuration Parameters		
Size – First Hidden Layer	**20**	**35**
Size – Second Hidden Layer	**25**	**35**
Size – Third Hidden Layer	**Has two hidden layers**	**20**
Transfer function- First Hidden Layer	***Logsig***	***Logsig***
Transfer function- Second Hidden Layer	***Logsig***	***Logsig***
Transfer function – Third Hidden Layer	**-**	***Tansig***
Bias Connection Configuration		
First Hidden Layer	***No***	***Yes***
Second Hidden Layer	***No***	***Yes***
Third Hidden Layer	**-**	***No***
Data Division Proportion		
Training Data	***80%***	***80%***
Validation Data	***5%***	***10%***
Testing Data	***15%***	***10%***
Additional Training Configuration Information		
Training Algorithm	***Levenberg-Marquadt***	***Gradient Descent with Momentum***
Regularisation	$\mathbf{8.9x10^{-2}}$	$\mathbf{1.0x10^{-4}}$

MATLAB uses the training, validation and testing sets to train the ANN [89]. The training set is initially used to adapt the ANN weights to achieve a specified prediction mean-square error. Training is deemed to be adequate, if the training mean-square error continuously reduces. The validation set is used to monitor training and prevent poor generalisation. In a well-trained ANN, poor generalisation can be deemed avoided if the validation mean-square error is smaller than the training mean-square error. The testing dataset is used to verify the appropriateness of the data division. In the case where the testing and validation mean-square error reach their minimum in closely spaced epochs, the data division is deemed correct. These requirements are met in the performance of NN 1 and NN 2 in Figures 3-9 and 3-10, respectively. Figures 3-9 and 3-10 show the training, validation and testing of mean-square error of NN 1 and NN 2, respectively. It can be seen that NN 1 and NN 2 are well-trained; because the conditions above are met.

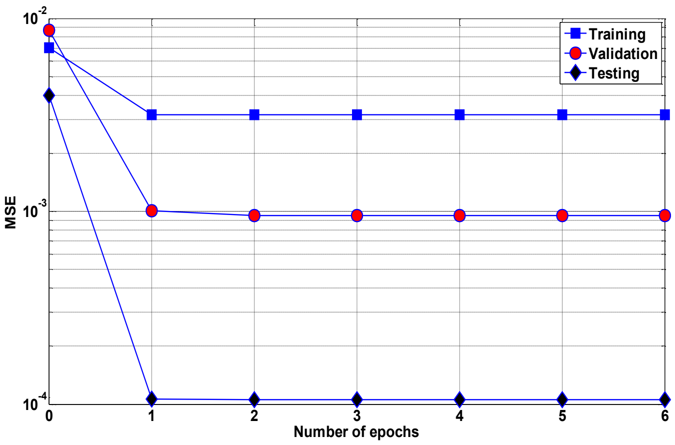

Figure 3-9: NN 1 training performance.

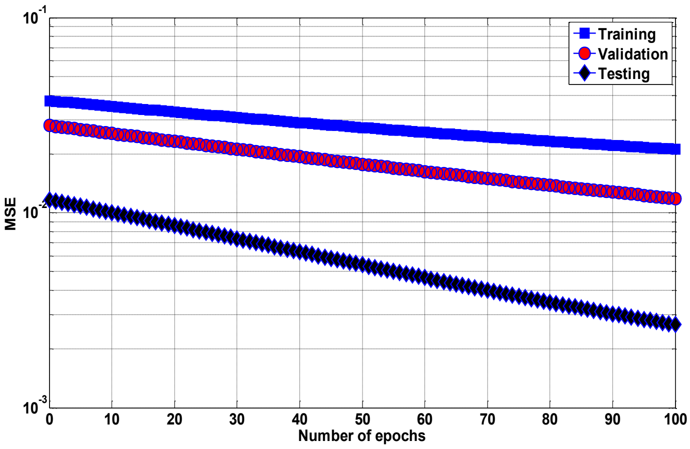

Figure 3-10: NN 2 training performance.

Post-processing is used to enhance the prediction performance. Extensive simulations show that C_{τ}^{PU} prediction is enhanced by multiplying the predicted output by 1.055. The duty cycle describes the PU channel usage. A scenario where SUs seek to opportunistically bond with channels that are not frequently used by PUs, has been considered. These channels are bonded with those of low C_{τ}^{PU}. This upholds the CPP but leads to channel underutilisation. The comparison of predicted and expected duty cycles is shown in Figure 3-11. NN 2 predicts T_{con}. Post-processing tasks are applied to enhance the NN 2's predicted performance by multiplying the output by 0.70. A comparison of the predicted and expected connection duration is shown in Figure 3-12.

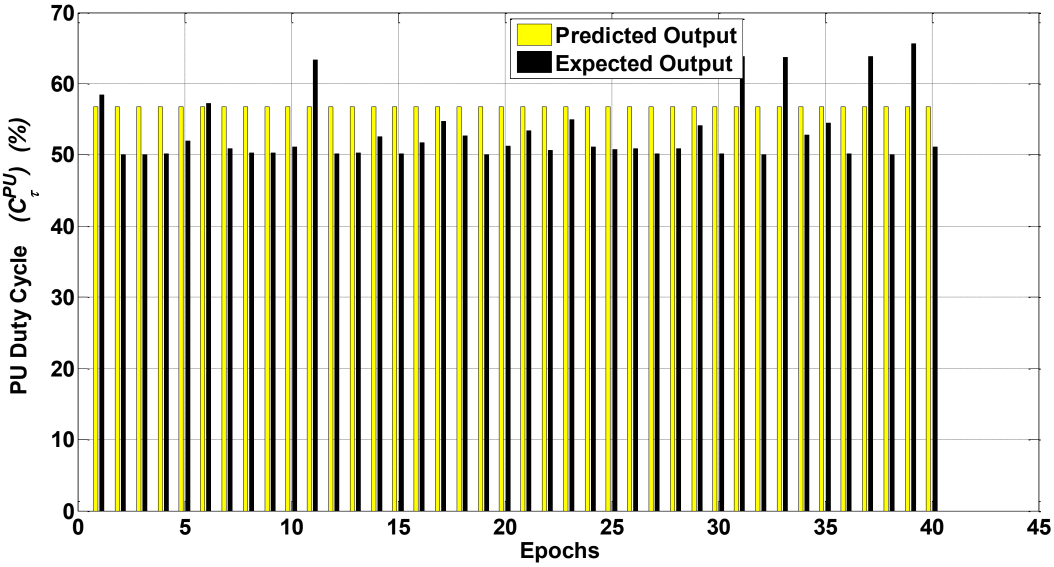

Figure 3-11: Duty cycle comparison (NN 1).

Figure 3-11 shows that CRs using NN 1 have a duty-cycle prediction that falls short of the actual PU usage in 6 epochs out of 40 epochs. In these 6 epochs, the CR underestimates PU spectrum usage and it poses an interference threat to PUs. NN 1's collision and non-collision probabilities are 0.15 and 0.85, respectively.

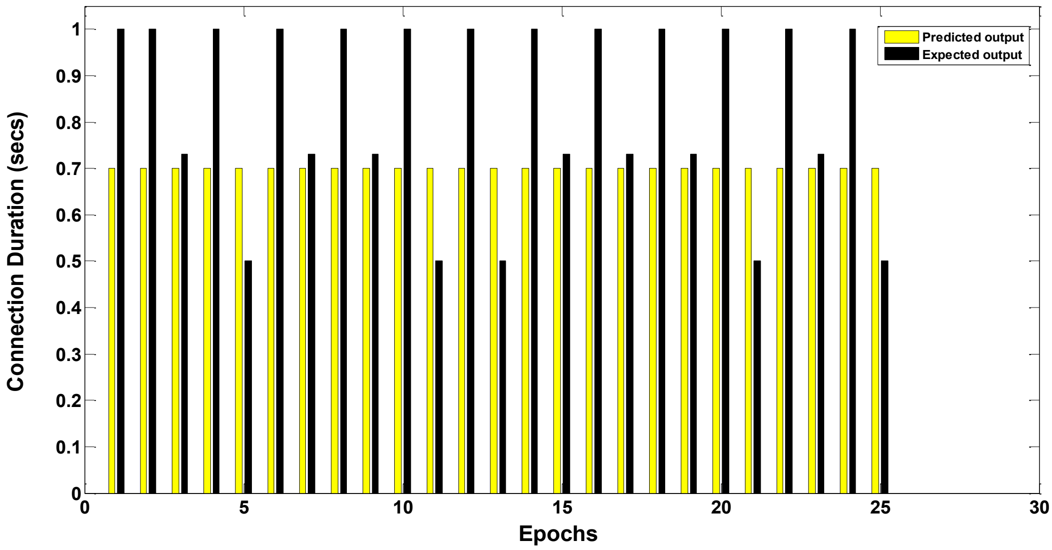

Figure 3-12: Connection duration (NN 2).

Figure 3-12 shows a comparison of predicted and expected connection duration over 25 epochs. The CPP is contravened and CRs interfere with PUs, when the predicted connection duration exceeds the expected connection duration. Investigation shows that the CR-PU collision probability is 0.20 (when the predicted output exceeds the expected output). The non-collision probability is 0.80 (when the predicted output equals or is less than the expected output).

The CR throughput is simulated by using parameters in Table 3-4 for four cases. In the first case, the CR uses the existing CSIT and experiences interference from two neighbouring users. In the second, the CR uses the proposed mechanism (heterogeneous mode) and experiences interference from two neighbouring users. The scenario described in the third considers a CR that uses the existing CSIT and experiences interference from four neighbouring users. The fourth describes a CR that uses the proposed mechanism (heterogeneous mode) and experiences interference from four neighbouring users. The simulated throughput is shown in Figure 3-13. The proposed mechanism (heterogeneous mode) enhances CR throughput by 4.5% and 7.5% given two and four neighbouring users, respectively.

Table 3-4: LTE-Advanced transmit channel parameters

Parameter	Value
Number of Paths	6
Number of Sub paths	20
Number of eNB and CR antenna elements	6
Mean antenna inter-element distance (eNB)	20.8cm
Mean antenna inter-element distance (CR)	16.7mm
Orientation of eNB with respect to CR	60 deg
Mean CR transmit power	8.8 mW
Mean increase in CR transmit power	21.5%
Data Channel Bandwidth	1.25MHz

The spectrum utilisation in bps/Hz is also simulated and shown in Figure 3-14. Results presented in Figure 3-14 show that the proposed mechanism (heterogeneous mode) enhances the spectrum utilisation (bps/Hz). This is because of the higher throughput in the CR that uses the proposed mechanism (heterogeneous mode) compared to CSIT.

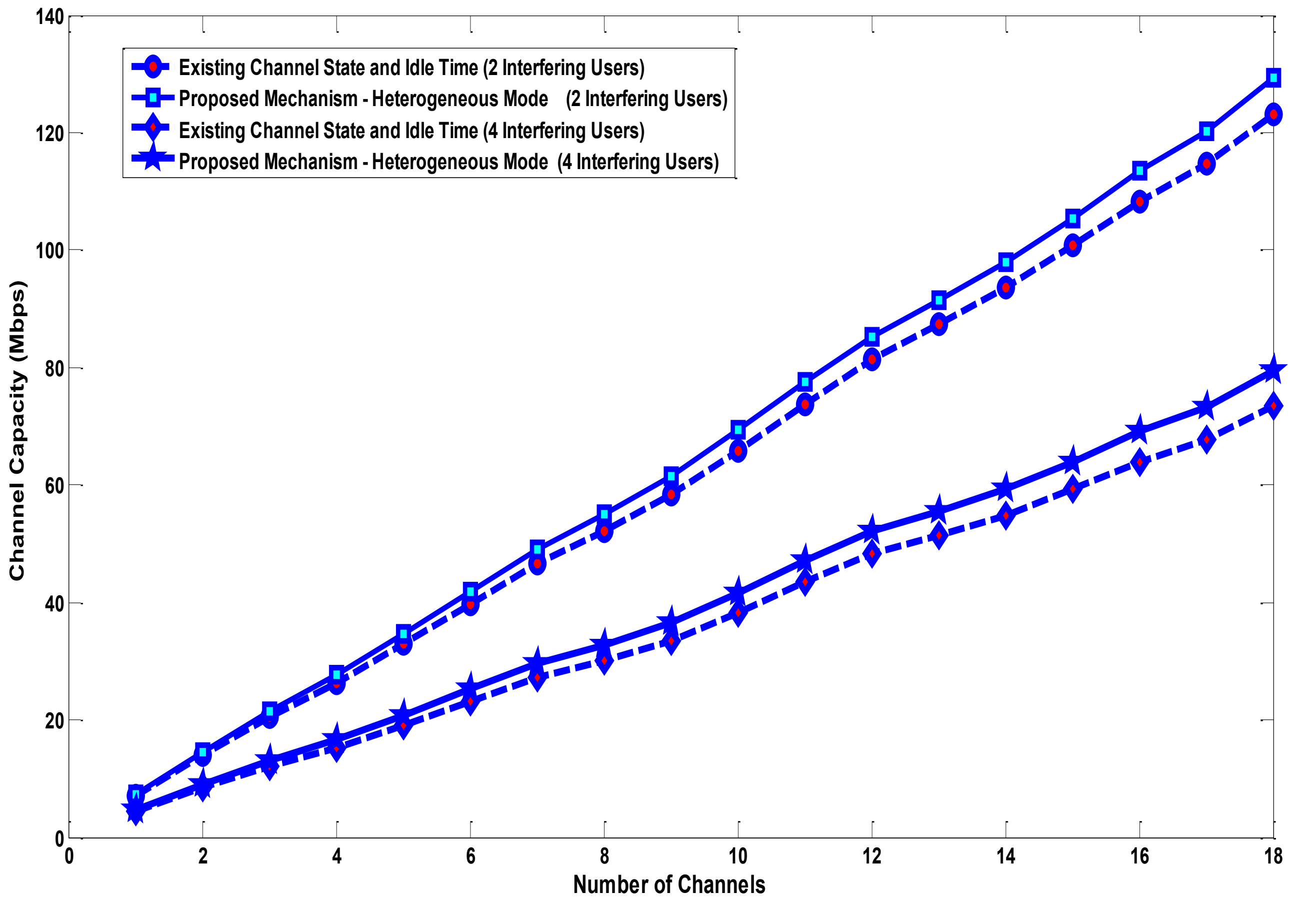

Figure 3-13: Cognitive radio channel capacity.

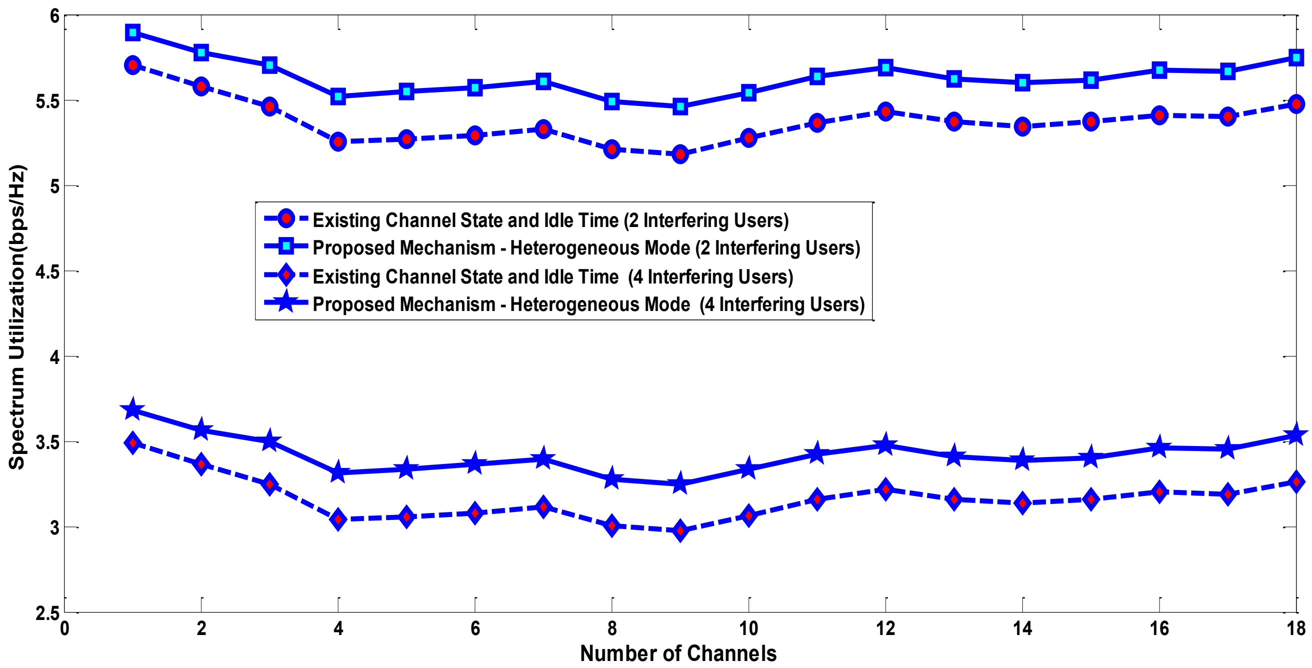

Figure 3-14: Cognitive radio spectrum utilisation (bps/Hz).

The data transmitted when the CR using the proposed mechanism (heterogeneous mode) and CSIT is shown in Figure 3-15. In Figure 3-15, the throughput is the amount of data transmitted by the CR. The CR using the proposed mechanism (heterogeneous mode) has an enhanced throughput compared to the CR using CSIT. The throughput of the CR using the proposed mechanism exceeds that of the CR using CSIT by 36% on average. The dual mode CR throughput (heterogeneous mode) exceeds the single mode CR throughput (homogeneous mode) by 5% on average. The throughput of the dual mode CR exceeds that of the single mode CR using CSIT by 12% on average. The throughput improvement is due to the concurrent capability of the dual mode CR.

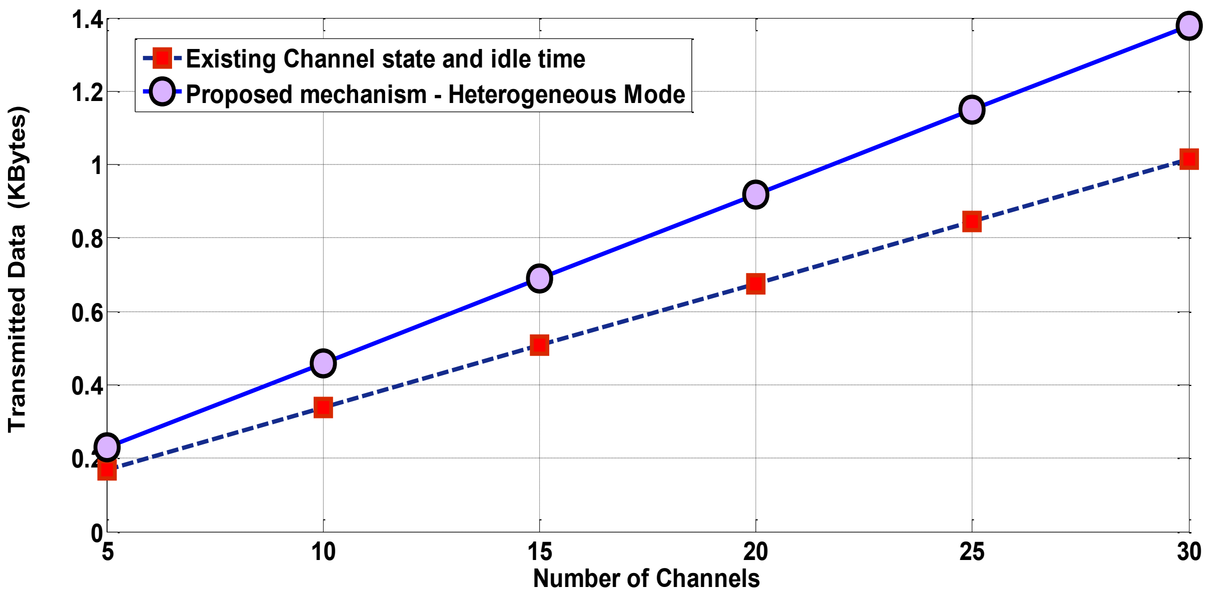

Figure 3-15: Throughput performance and benefit of the proposed mechanism (heterogeneous mode).

NN 1 and NN 2 can be used on CR with RAM of up to 1.5 GB. NN 1 uses an average RAM of 970 MB for 4.073 seconds during training. NN 2 uses an average of 899.8 MB RAM for 0.256 seconds during training. If an ensemble neural network architecture comprising multiple NN1 and NN 2 blocks were used, the required resources increase. The CR requires 4GB of RAM and the CC-FNN development takes 4.329 seconds.

The simulation also investigates the packet loss rate. The aim is to demonstrate that the CR using the proposed mechanism (heterogeneous mode) has a reduced PLR compared to the CR using CSIT. The values of $P_{md}^{b'}$ and parameter prediction probability in the simulation are 0.06 and 0.12, respectively. The PLR performance is shown in Figure 3-16. Figure 3-16 shows that CR using the proposed mechanism (heterogeneous mode) have a low PLR compared to a CR using CSIT. This is because the proposed mechanism (heterogeneous mode) improves CR channel awareness status.

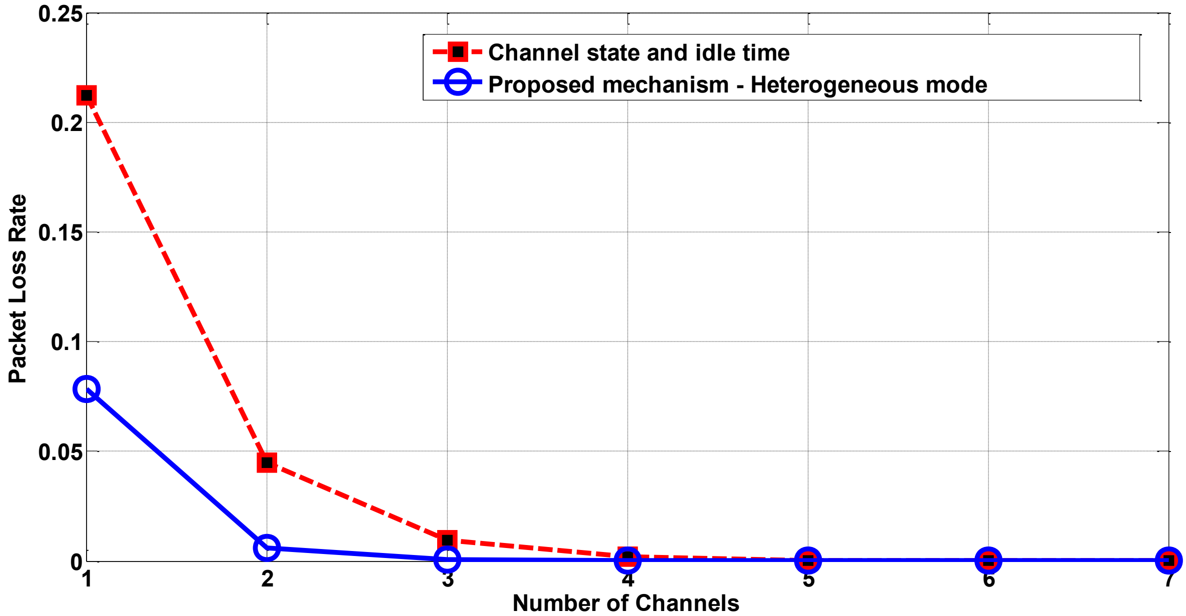

Figure 3-16: Packet loss.

The signalling overhead refers to the time spent acquiring training data by a cognitive radio from neighbouring cognitive radios. The use of the proposed mechanism reduces the overhead by enabling CR transmission for a longer duration instead of spending more time acquiring neural network training data. Hence, the overhead is described in spent acquiring training data.

This concern has been addressed and clarified by explaining the role of the signalling overhead in the first sentence after Figure 3-16. Hence, signalling overhead as used in Figure 3-16 can be interpreted to be time spent acquiring training data and measurable in seconds.

The signalling overhead is examined for three scenarios i.e. scenarios 1, 2 and 3. Scenario 1 considers a single mode CR using CSIT. Scenario 2 considers a single mode CR using the proposed mechanism (homogeneous mode). Scenario 3 considers the CR using proposed mechanism (heterogeneous mode). In the simulation, the CR transmits data via one RAT. The dual mode CR has not been considered here because data transmission and sensing are being considered to occur separately.

The incorporation of the proposed mechanism (homogeneous mode) reduces the MGL by 1.5ms. The mean training data acquisition duration is 3.9ms. The mean data transmit duration of CRs in LTE-A is 21.4ms. The simulated signalling overhead for scenarios 1, 2, and 3 is shown in Figure 3-17.

From Figure 3-17, it can be seen that scenario 3 has the lowest signalling overhead when compared with scenario 1 and scenario 2. There is zero-signalling overhead in the heterogeneous mode, when there are 3, 4 and 5 neighbouring CRs. The signalling overhead is null because the CR benefits from the ISH. ISH is not incorporated in CSIT and proposed mechanism (homogeneous mode). The signalling overhead of the CR using CSIT exceeds the signalling overhead of the CR using proposed mechanism (homogeneous mode). The proposed mechanism (homogeneous mode) has a lower overhead than CSIT due to the NSC. The NSC is used to detect quasi-mobile TWN states. In CSIT, the CR has to complete the acquisition of the training data; it does not check for the validity of the NSC and does not use ISH.

Investigations show that the proposed mechanism (homogeneous mode) reduce the signalling overhead by 38% on average when compared to CSIT. The proposed mechanism (heterogeneous mode) reduces the signalling overhead by 62% on average when compared to CSIT. Hence, the incorporation of the proposed NSC and ISH reduces signalling overheads. In addition, the proposed mechanism reduces the signalling overhead in HWNs. The CR in heterogeneous mode has a signalling overhead that is 24% lower than the CR in homogeneous mode.

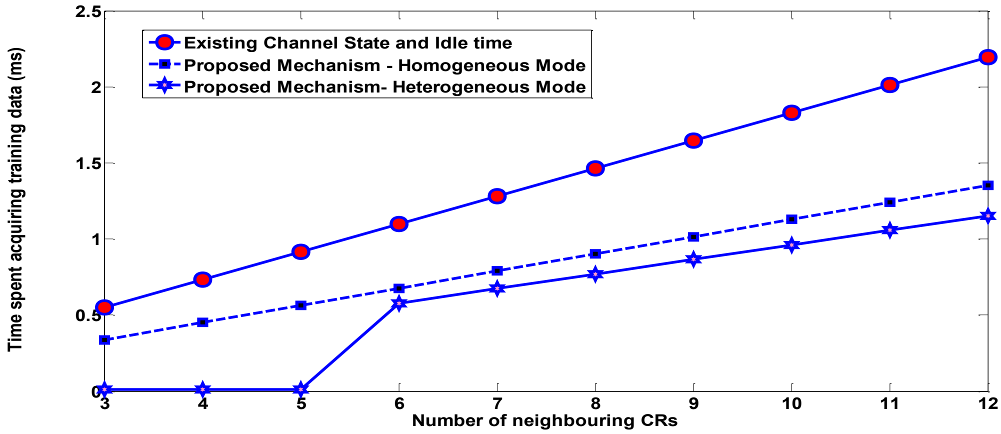

Figure 3-17: Cognitive radio time spent acquiring training data.

3.6 Conclusion

This chapter has proposed a mechanism that enhances CR performance in homogeneous and heterogeneous TWNs. The proposed mechanism satisfies the goals of future generation-wireless networks by enhancing CR QoS and reducing signalling overhead. The reduction of signalling overheads ensures that a larger portion of the TWN allocated spectrum is used for data transmission. A reduced signalling overhead implies that spectrum that could have been allocated for overheads is made available for other technologies requiring spectrum access.

The next chapter addresses another goal of the unified service architecture. The goal addressed in the next chapter is enhancing the QoS of a CR that uses multiple-learning algorithms.

Chapter 4

Mechanism for Enhancing the QoS of CRs with Learning Diversity

The previous chapter presented a dual mode mechanism that reduces CR overhead in TWNs. The reduced overhead enables the CR to devote more spectral resources to data transmission. This is achieved considering similarities in the TWN environment. The spectral resources that would have been used for overhead signalling are made available for other technologies requiring spectrum access. In addition, the proposed mechanism satisfies the goal of the unified architecture by improving the subscribers' QoS. However, the mechanism in chapter 3 has not considered how to enhance the QoS of subscribers that use learning diversity.

Learning diversity is the CR's ability to use multiple learning algorithms (LAs) to achieve a spectrum prediction objective. The use of multiple LAs enables the CR to determine the best LA for a given scenario and epoch. The multiple LAs can be different ANN architectures. A CR with learning diversity can have meta-cognitive capability. Meta-cognition is the CR's ability to classify and select the best LA at different epochs in the network. In addition, the CR with meta-cognition also regards the LAs as part of the CR's configuration parameters. The focus of this chapter is on enhancing the QoS of LTE-A subscribers i.e. CRs that incorporate learning diversity. The section is divided into six parts. The first part discusses related work. The second and third describe the problem and proposed mechanisms, respectively. The fourth and fifth focus on performance formulation and presents evaluation results, respectively. The sixth is the conclusion.

4.1 Related Work

The notion of a CR that incorporates meta-cognition is introduced in [90-91]. A CR with meta-cognition can develop capabilities enabling the satisfaction of the goals of the unified architecture in new scenarios. The discussion in this chapter focuses on scenarios not considered in Chapter 3.

The incorporation of ANNs in CRs enables the CR to bring the benefits of artificial intelligence to TWNs. The benefits of artificial intelligence that can be harnessed in CRs can be enhanced via meta-cognition. The discussion in this chapter investigates how meta-cognition can enhance CR-QoS. In this chapter, the CR comprises multiple LAs and the benefits that can be derived from learning diversity. The LAs need not be RAT-specific; and are used for different tasks that require spectrum prediction. In this context, spectrum prediction refers to the use of trained LAs to compute CR transmission parameters in licensed spectrum. The use of multiple LAs enhances CR contextual awareness. The mechanisms proposed in this chapter aim to enhance CR QoS in line with the goals of the unified architecture.

CRs with bio-inspired techniques have been considered for learning [22] , spectrum prediction [23] and RAT classification [51]. Intelligent algorithms furnish the host entity with the capability to adapt to environmental changes. The incorporation of cognition enables an entity to think on adapting to a changing environment. The adaptive capacity of entities can be further enhanced by meta-cognition. A meta-cognitive entity can use its thinking process and thought patterns as a parameter. A CR with meta-cognitive capability is proposed in [90-91].

Asadi *et al.* [90-91] propose a meta-cognition engine that enables CRs to benefit from learning diversity. Learning diversity enables CRs to combine the strengths of different LAs, while minimizing their weaknesses during spectrum prediction. LAs can be classified by using the CR QoS at an epoch in the proposed best-classification algorithm [90]. The incorporation of meta-cognition enables CRs to become LA aware [90-91].

4.2 Problem Description

This section describes the problems being addressed in this chapter and uses the parameters in Figure 4-1.

Table 4-1: List of parameters used in this chapter.

$\mathfrak{L}(t)$	Set of learning algorithms (LAs) in CR that incorporates learning diversity at instant t.
$Q(t)$	Set of observed CR QoS for LA in CR that incorporates learning diversity at instant t.
P	Initial battery power for CR that incorporates learning diversity
r	Set of cognition engines (CEs) in the CR that incorporates learning diversity.
r_u	The CR's u^{th} CE.
$P_{ta}(\mathfrak{L}(t))$	CR battery power expended in training LAs in the CR that incorporates learning diversity at instant, t.
$P_{cl}(\mathfrak{L}(t))$	CR battery power expended in classifying LAs in CR that incorporates learning diversity at instant, t.
$P_{ta}\left(\mathfrak{L}_q(t_p)\right)$	CR battery power expended in training LA $\mathfrak{L}_q$at instant t_p ; $\mathfrak{L}_q(t_p) \epsilon\ \mathfrak{L}(t)$
$P_{cl}\left(\mathfrak{L}_q(t_p)\right)$	CR battery power expended in classifying $\mathfrak{L}_q$at instant t_p.
$P_{tr}(\mathfrak{L}_q(t_p))$	CR data transmit power when CR uses a LAs at instant t_p.
$I_q(t)$	Best LA indicator signifying that an LA is the best for CR spectrum prediction at instant t.
$P'_{tr}(\mathfrak{L}_q(t_p))$	Data transmit power when CR uses LDS at instant $t_{p'}$.
T_q^{ta}	LA training duration for the LA q in the CR that incorporates learning diversity.
ϑ	Transmit duration of CR that incorporates learning diversity with existing mechanism.
ϑ'	Transmit duration of CR that incorporates learning diversity with proposed LDS.
$P_{b'}^1$	Data transmit power on $c_{b'}$ for CR with learning diversity but without LDS.
$P_{b'}^2$	Data transmit power on $c_{b'}$ for CR with learning diversity with LDS.
Th_1	Throughput of CR with learning diversity but without LDS.
Th_2	Throughput of CR with learning diversity with LDS.
D_1	Amount of data transmitted when CR does not use LDS.
D_2	Amount of data transmitted when CR uses LDS.
r	Set of cognition engines (CEs) in CR that use LCP.
N_{LA}^u	Number of LAs in r_u ; $r_u \epsilon\ r$.
θ_u^v	Number of connections between r_u and r_v ; $r_v \epsilon\ r$
ψ_1	Number of CEs connected to r_1
ρ_1	Number of layers between r_1 and CR's resources
Ω	CR- Price of Maintaining Consciousness in CR that uses existing mechanism.
Ł	Reduction in CR transmit power.
N_p^u	Number of CR's paused CEs in r_u.
N_T	Total number of CR's CE layers
µ	Pause-transfer efficiency.
P	Initial CR data transmit power.
P'	Data transmit power of CR that incorporates learning diversity and uses LCP.
Ω''	CR- PMC of CR that engages in spectrum sharing and uses existing mechanism i.e. without LCP.
P''	Transmit power of CR with learning diversity that engages in spectrum sharing and incorporates LCP.
$P_{b'}^{A_1}$	Data transmit power of CR that does not engage in spectrum sharing and does not incorporate LCP.
$P_{b'}^{A_2}$	Data transmit power of CR that does not engage in spectrum sharing and uses LCP
$P_{b'}^{A_3}$	Data transmit power of CR that does engages in spectrum sharing and uses LCP
Th_{A_1}	Throughput of CR that does not engage in spectrum sharing and does not use LCP
Th_{A_2}	Data transmit throughput of CR that does not engage in spectrum sharing and uses LCP
Th_{A_3}	Data transmit throughput of CR that engages in spectrum sharing and uses LCP

The scenario being considered comprises PUs and CRs, i.e. SUs in licensed spectrum infrastructure based TWN. PUs-CRs relations do not contravene the CPP. Let $\mathfrak{L}(t)$ and $Q(t)$ be the set of LAs and observed CR QoS with each LA at instant t, respectively.

$$\mathfrak{L}(t) = \{\mathfrak{L}_1(t), \mathfrak{L}_2(t), \dots, \mathfrak{L}_{\mathbb{N}}(t)\} \tag{4.1}$$

$$Q(t) = \{Q_1(t), Q_2(t), \dots, Q_{\mathbb{N}}(t)\} \tag{4.2}$$

In addition, let P and $P_{ta}(\mathfrak{L}(t))$ be the initial CR battery power and the CR battery power expended in LA training, respectively. Furthermore, let $P_{cl}(\mathfrak{L}(t))$ be the CR power expended on LA classification. The CR's LAs are classified by using CR QoS. The CR QoS is determined for each LA's spectrum prediction procedure.

The CR holds information on the observed transmit parameters for different network scenarios. This information is used to train the CR's LAs (when the CR incorporates learning diversity). In the TWN, the CR incorporating learning diversity seeks to train multiple LAs prior to spectrum prediction and data transmission. The training of each LA consumes CR battery power and reduces CR data transmit power. The training of multiple LAs at epoch t_p $\left(t_p \epsilon\, t\right)$ prevents CR data transmission when:

$$P - \sum_{q=1}^{\mathbb{N}} P_{ta}\left(\mathfrak{L}_q(t_p)\right) \leq 0\,; \left(\mathfrak{L}_q(t_p)\ \epsilon\ \mathfrak{L}(t)\right) \tag{4.3}$$

The CR uses an LA for spectrum prediction and data transmission to enhance the CR QoS in the TWN. The CR seeks to use the best LA (determined via LA classification) for spectrum prediction. The CR has information on the achieved QoS when each LA is used for spectrum prediction. The CR QoS is used to classify LAs across multiple epochs. During LA classification, the CR is unaware of the desire of the TWN subscriber to transmit data. The classification expends the CR battery and reduces CR battery capacity available for data transmission by the subscriber. LA classification prevents data transmission when the energy required for LA classification equals or exceeds the available CR battery power capacity. This arises at epoch t_p when:

$$P - \sum_{q=1}^{\mathbb{N}} P_{cl}\left(\mathfrak{L}_q(t_p)\right) \leq 0\,; \left(\mathfrak{L}_q(t_p)\ \epsilon\ \mathfrak{L}(t)\right) \tag{4.4}$$

(4.3) and (4.4) describe the case when CR battery power is expended by LA training and classification, respectively. The challenge in (4.3) arises because the CR is expected to train all its LAs prior to spectrum prediction and CR data transmission. The challenge in (4.4) arises because the CR classifies LAs, without checking whether the CR wants to send data. This chapter addresses the challenges in (4.3) and (4.4).

4.3 Proposed Mechanism

This section discusses the mechanism proposed to address the challenges in (4.3) and (4.4). The proposed mechanism incorporates the features of learning diversity selection (LDS) and LA classification pause (LCP).

It is divided into two parts. The first part discusses LDS proposed to address the challenge in (4.3). The second discusses LCP proposed to address the challenge in (4.4).

4.3.1 Learning-Diversity Selection (LDS)

LDS is proposed to enable the CR to reduce the battery power expended in LA training. The TWN is considered to have two types of CRs. These are existing CRs and incoming CRs. Existing CRs have completed data transmission by using the parameters determined by trained LAs via spectrum prediction. The information on the LA and achieved CR LA QoS are sent to the LTE-An eNB. The existing CR to LTE-A eNB transmission occurs via the dedicated control channel (DCCH) at the expiration of the measurement gap repetition period (MGRP). The eNB receives LA information and achieved QoS from existing CRs. The received information is used to rank LAs. The LA-ranking information is sent by the eNB to the incoming CR via the EPDCCH. Interactions between existing CRs, eNB and incoming CRs are shown in Figure 4-1. In Figure 4-1, there are three existing CRs and two incoming CRs. The existing CRs are ECR_1, ECR_2 and ECR_3. The two incomfing CRs are ICR_1 and ICR_2. LA ranking information is transmitted by ECR_1, ECR_2 and ECR_3 to the eNB at epochs t_1, t_2 and $t_{3,}$, respectively. The eNB ranks the LAs during epochs t_4 and t_5. LA ranking information is sent from the eNB to ICR_1 and ICR_2 at epochs t_6 and t_7, respectively.

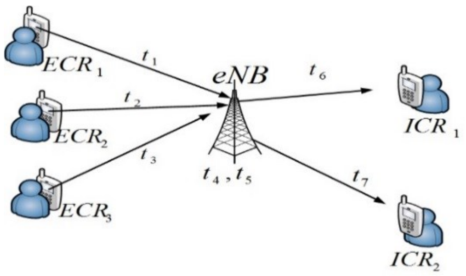

Figure 4-1: Interaction between existing cognitive radios, evolved Node B and incoming cognitive radios.

The incoming CR can also acquire information used for LA ranking directly from neighbouring existing CRs. However, this option has not been considered because of the additional power expended by incoming CRs in ranking LAs. Moreover, the eNB can access data from more exsitng CRs; since all existing CR transmission goes through the eNB. LA ranking here denotes the classification of the LA, based on the existing CR QoS.

The LA training order and training data are obtained from the eNB by the incoming CR during the LTE-A MGL. The eNB transmits the LA training-order frame, as shown in Figure 4-2. The frame in Figure 4-2 considers N sub-channels in LTE-A at epoch 1. Each sub-channel has q LAs.

Training Data			
Sub Channel 1 ...		Sub Channel N	
LA 1 QoS	LA q QoS	LA 1 QoS	LA q QoS
Epoch 1		Epoch 1	
LA Training Order		LA Training Order	

Figure 4-2: Learning diversity selection training order framework.

The flowchart for executing LDS is shown in Figure 4-3. In Figure 4-3, an incoming CR receives the LDS frame from the eNB. The incoming CR searches the frame to see if all the LA information is available at the considered epoch. The incoming CR does not use sub-channels with missing LA data, to prevent CPP violation on concerned sub-channels. LDS is executed by an incoming CR in LTE-A. The existing CRs sends LA and QoS data to the eNB at the epoch of MGRP expiration in the RRC_CONNECTED state. The incoming CR receives the LA ranking information from the eNB during the MGL in the RRC_CONNECTED state.

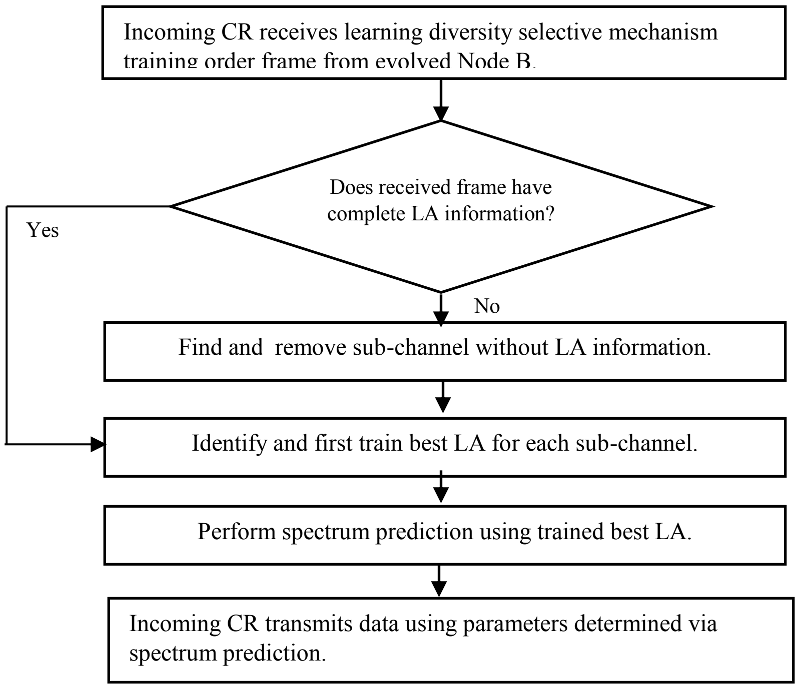

Figure 4-3: Learning diversity selection flowchart.

4.3.2. LA Classification Pause (LCP)

The proposed LCP uses concepts from the integrated theory of consciousness [92] and nervous system evolution [93-94]. The integrated information theory identifies the claustrum as being responsible for consciousness. The claustrum has been identified to be responsible for the brain's consciousness [95].

Nervous-system evolution studies how environmental pressures influence nervous system development. From [93], it can be inferred that nervous system development can be temporarily frozen. The freezing enables the organisms to redirect their resources towards other important metabolic tasks. This thesis uses concepts from nervous system evolution to achieve LCP. It proposes that access to the CR's resources (cortex) should be controlled by an electronic claustrum. The electronic claustrum ensures that data transmission (important metabolic task) is not impaired. The CR that pauses LCP has multiple cognition engines (CEs) with multiple LAs; and is shown in Figure 4-4. LA training and classification in a CE is controlled by a decision-making layer (DML).

Each LA is connected to a DML. LA DMLs send their information to the CE DML. The CE DML classifies CR task-specific LAs. Prediction tasks that can enhance CR QoS are described in [47-48, 50-51]. Spectrum prediction can be used to enhance CR QoS in different ways. These examples are cited here for the sake of clarifying the discussion.

Figure 4-4 shows a CR with $\mathcal{M}$ CEs – each having $\mathcal{N}$ LAs. Each LA has a DML. Each CE has a DML, i.e. the CE-DML. The CE-DML is linked to all the LA-DMLs, i.e. DML 1 and DML $\mathcal{N}$. The CE-DML uses information on the LA-DMLs to classify the LAs. The LCP's flowchart is shown in Figure 4-5. In Figure 4-5, it is assumed that the CR has an LA granularity and can monitor the power consumed per DML.

The CR monitors battery power utilisation, checks to see whether there is ongoing LA classification; and if (4.5) holds true. The CR pauses the CE-DML and all links between LA-DMLs and the CE-DML. The CE-DML retains the information on the current state of classification. LA classification is resumed after the completion of the data transmission. During the pause, the CR uses the LA that is most identified in previous epochs to achieve the best QoS. Connections between CEs and LAs enables the exchange of training information via intra-CE and inter-CE relations.

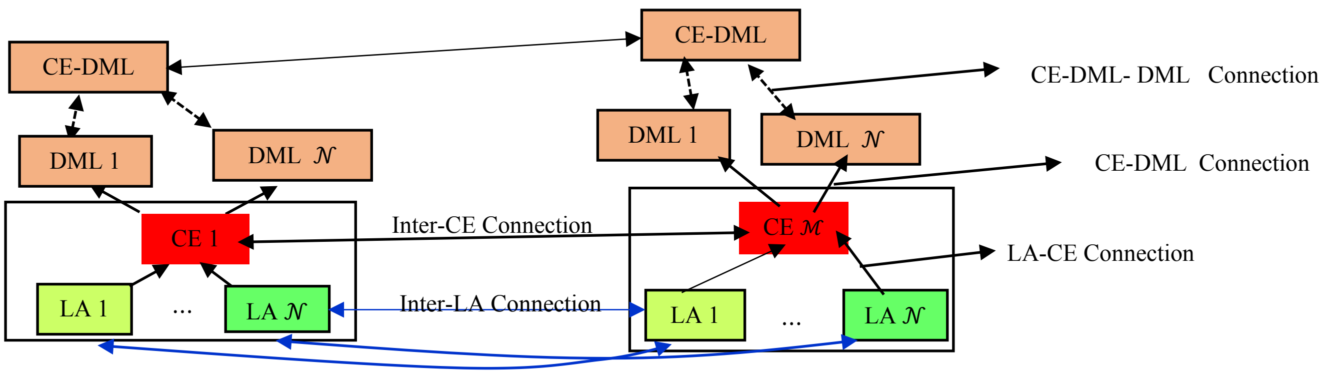

Figure 4-4: Architecture of the cognitive radio incorporating learning classification pause.

The architecture shown in Figure 4-4 comprises the inter-LA, LA-CE , CE-DML and DML- CE DML connections. These connections consume CR battery power.

Inter-CE connections enable the exchange of training and performance information between LAs of similar architectures that are used for different tasks. The exchange of such information enables the CR to develop a profile of how a given LA improves the QoS when used for spectrum prediction. Spectrum prediction is the determination of CR transmit parameters using a trained LA in a given network scenario.

LA-CE connections enables the CR to observe the achieved QoS when different LAs in a CE are used for spectrum prediction.

CE-DML connections are used to make classification decisions on each LA using CR QoS information. The DML-CE DML connections enables the CR to make a decision as regards pausing LA classification. The CE-DML sends pause instructions to specific LAs.

The pause proposed in LCP is realised in the RRC_COGNITIVE state. Online LA classification via the DML takes place in the RRC_CONNECTED state during the MGL. CR LA classification via the DML can also take place off-line in the RRC_IDLE state. Training data acquisition and LA training occurs in the RRC_IDLE state.

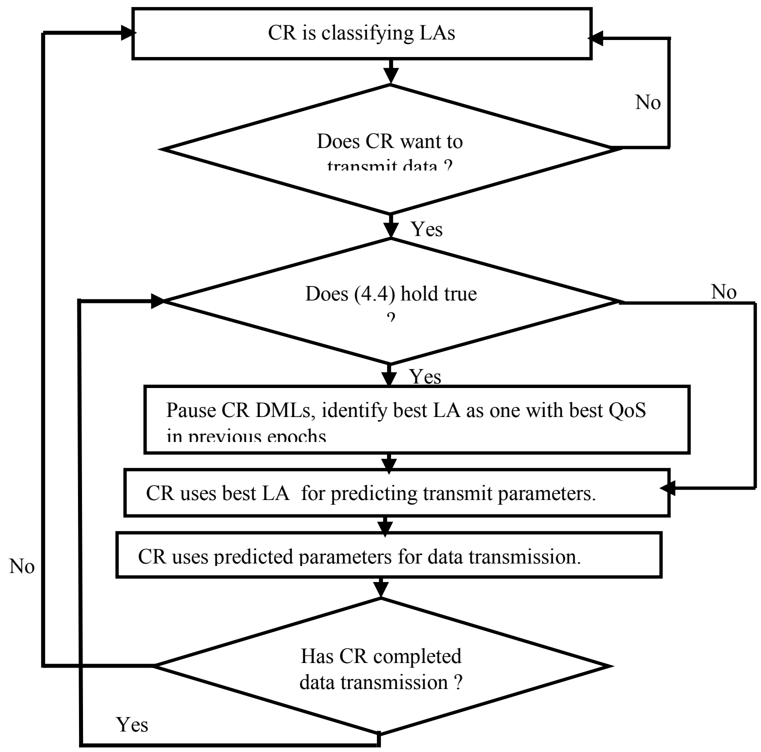

Figure 4-5: Flowchart for the learning algorithm classification pause process.

Spectrum prediction is done by trained LAs during the MGL in the RRC_CONNECTED state. The CR spectrum prediction is done directly by LAs. The pause of the LA classification in either the RRC_IDLE or RRC_CONNECTED results in a transition to the RRC_COGNITIVE state. The CR incorporating LCP carries out five tasks across the RRC_IDLE, RRC_CONNECTED and RRC_COGNITIVE states. These tasks are: training-data acquisition (A), LA training (B), spectrum prediction (C), data transmission (D) and classification (E). The execution of these tasks by the CR in the three states is shown in Figure 4-6.

In Figure 4-6, the three states, i.e. RRC_IDLE, RRC_CONNECTED and RRC_COGNITIVE states are non-overlapping in the CR. The CR executes tasks A, B, E in the RRC_IDLE state. It executes tasks C and D in the RRC_CONNECTED MGL and DTT, respectively. The CR transits from RRC_IDLE to RRC_CONNECTED MGL and from MGL to DTT in RRC_CONNECTED state. In addition, the CR can also transit to the RRC_IDLE state, after exiting the RRC_CONNECTED state. The results of the achieved CR

QoS are then used to execute task E in the RRC_IDLE state. The CR transits from RRC_IDLE to the RRC_COGNITIVE state, if LA classification is ongoing and CR desires to transmit data.

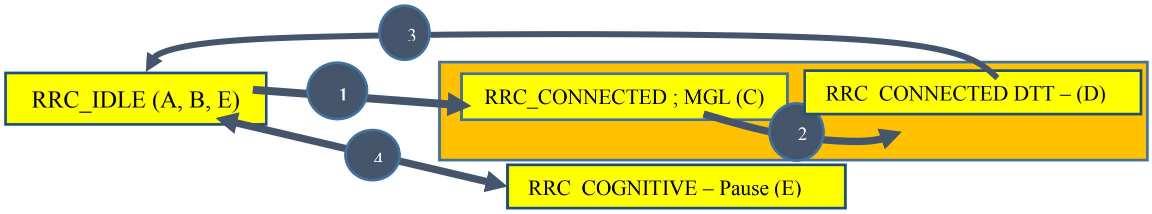

Figure 4-6: Relations between the RRC_IDLE, RRC_CONNECTED and RRC_COGNITIVE states.

4.4 Performance Formulation

This section formulates the performance model for the cases where the CR executes LDS and LCP. The metrics for LDS are (1) CR transmit power, (2) CR-channel capacity, (3) CR-data transmit duration and (4) CR-transmitted bytes. The performance metrics for LCP are CR-transmit power and CR-channel capacity. The metrics for LDS and LCP are different; because they are used in different scenarios. In the case of LDS, CR-transmit duration, CR-transmitted bytes are considered; because the LA training is done in the MGL. The execution of LA training can exceed the MGL, thereby affecting CR-transmit duration. A varying CR-transmit duration also influences CR-transmitted bytes. Hence, CR-transmit duration and CR-transmitted bytes are additionally considered in the LDS.

The transitions in Figure 4-6 do not affect the MGL and the CR- transmitted bytes, which is dependent on the CR-transmit duration. Hence, the CR-transmit duration and the CR- transmitted bytes are not investigated in the LCP. LCP also introduces the notion of the CR's price of maintaining consciousness. The CR's price of maintaining consciousness is the total number of links between DMLs of LAs and CEs that use CR resources during LA classification.

The discussion in this section is divided into two parts. The first and second parts present the LDS and LCP performance models,respectively.

4.4.1 Learning Diversity Selection -Performance Formulation

Given that the CR has $\mathbb{N}$ LAs at epoch t_p , the CR-transmit power, $\left(P_{tr}\left(\mathfrak{L}\left(t_p\right)\right)\right)$ can be computed as:

$$P_{tr}\left(\mathfrak{L}\left(t_p\right)\right) = P - \sum_{q=1}^{\mathbb{N}} P_{ta}\left(\mathfrak{L}_q\left(t_p\right)\right);\ \mathfrak{L}_q\left(t_p\right) \epsilon\ \mathfrak{L}(t) \qquad (4.5)$$

The incorporation of LDS enables the CR to identify the best LA. Let $I_q(t)\ \epsilon\ \{0,1\}$ be the best LA indicator at instant t. $I_q(t) = 0$ and $I_q(t) = 1$ signify that $\mathfrak{L}_q(t)$; $(\mathfrak{L}_q(t)\ \epsilon\ \mathfrak{L}(t))$ i.e. $\mathfrak{L}_q$ is the non-best and the best LAs at instant t, respectively. The CR-transmit power after LDS incorporation, $P'_{tr}\left(\mathfrak{L}\left(t_p\right)\right)$ at instant t_p is:

$$P'_{tr}(\mathfrak{L}(t_p)) = P - \sum_{q=1}^{\mathbb{N}} I_q(t_p) P_{ta}(\mathfrak{L}_q(t_p)) ; \mathfrak{L}_q(t_p) \epsilon\, \mathfrak{L}(t) \tag{4.6}$$

Let the LA training duration be T_q^{ta} for the $(q)^{th}$ LA. The CR-transmit duration in the absence of LDS, ϑ is:

$$\vartheta = S_M - \sum_{q=1}^{\mathbb{N}} T_q^{ta} \tag{4.7}$$

The CR-transmit duration at instant t_p after LDS incorporation, ϑ' is:

$$\vartheta' = S_M - \sum_{q=1}^{\mathbb{N}} I_q(t_p) T_q^{ta} \tag{4.8}$$

In formulating the CR-Th, the CR transmits over a channel subject to neighbouring user interference. Let $P_{b'}^1$ and $P_{b'}^2$ denote the CR transmission power on $c_{b'}$, without and with LDS, respectively. The CR-Th without and with LDS, is denoted as Th_1 and Th_2, respectively. Th_1 and Th_2 are computed as:

$$Th_{\mathrm{c}} = \sum_{b'=1}^{b} B_{b'} \log_2 \left(1 + \frac{P_{b'}^{\mathrm{c}} |h_{b'}^t|^2}{\left(|h_{b'}^{in}|^2 P_{b'}^{in}\right) + \sigma^2}\right) ; \mathrm{c}\, \epsilon\, \{1,2\} \tag{4.9}$$

$$\sum_{b'=1}^{b} P_{b'}^1 \leq \sum_{q=1}^{\mathbb{N}} P_{tr}\left(\mathfrak{L}_q(t_p)\right); \mathfrak{L}_q(t_p) \epsilon\, \mathfrak{L}(t) \tag{4.10}$$

$$\sum_{b'=1}^{b} P_{b'}^2 \leq \sum_{q=1}^{\mathbb{N}} P'_{tr}\left(\mathfrak{L}_q(t_p)\right) ; \mathfrak{L}_q(t_p) \epsilon\, \mathfrak{L}(t) \tag{4.11}$$

$\mathrm{c} = 1$ and $\mathrm{c} = 2$ denote the cases where CR does not incorporate and incorporates LDS, respectively.

The amount of data that can be transmitted by the CR without and with LDS is denoted as D_1 and D_2, respectively. D_1 and D_2 are:

.
$$D_1 = Th_1 \text{ x } \vartheta \tag{4.12}$$
$$D_2 = Th_2 \text{ x } \vartheta' \tag{4.13}$$

4.4.2. LA Classification Pause - Performance Formulation

For the purposes of the discussion here, the CR is assumed initially to be a PU. In this case, the use of LAs aims to improve the CR QoS. In LCP, the CR's consciousness is due to the connections between the LAs, the CEs and the corresponding DMLs. The CR's price of maintaining consciousness is formulated, assuming that the CR has interconnected learning algorithms (LAs) and cognition engines (CEs). The interconnection between LAs and CEs enable the sharing of information between task-specific LAs. Let $r\,; r = \{r_1, \dots, r_s\}$ be the set of CEs in a CR. In addition, let N_{LA}^u and θ_u^v be the (1) number of LAs in r_u ; $(r_u\, \epsilon\, r)$ and (2) number of inter- LA connections between CEs r_u and r_v ; $((r_v)\, \epsilon\, r)$. Furthermore, let ψ_u be the number of inter-CE connections in r_u. In formulating the CR's price of maintaining consciousness, it is assumed that the consciousness arises due to CEs and LAs inter-relations. In the absence of LCP, the CR's price of maintaining consciousness, Ω is:

$$\Omega = \sum_{u=1}^{s}(N_{LA}^{u} + \theta_{u}^{v}) + \sum_{u=1}^{s}\psi_{u} \;;\; u \neq v \tag{4.14}$$

The first term in (4.14) is the sum of the number of LAs in each CE and number of inter –LA connections between r_u and r_v. The second term is the number of inter-CE connections.

LCP enables the CR to control the number of active DMLs. Let N_p^u and N_T be the number of paused CEs in r_u and the total number of CR layers, respectively. The CR's price of maintaining consciousness after LCP incorporation, Ω' is:

$$\Omega' = \sum_{u=1}^{s}(N_{LA}^{u}) + \sum_{u=1}^{s}\left(\left(1 - \frac{N_p^u}{N_T}\right)(\theta_u^v + \psi_u)\right);\; N_p^u \leq N_T \,; u \neq v \tag{4.15}$$

In (4.15), the first term is the number of LAs in each CE. The second is the number of inter-CE and inter-LA connections that are active after LCP execution.

If P W is initially available for CR data transmission, the CR-transmit power when LCP is used, P' is:

$$P' = P + \mu(\Omega - \Omega') \tag{4.16}$$

$0 \leq \mu \leq 1$ is the pause-transfer efficiency. It determines the proportion of the difference in CR's price of maintaining consciousness used to increase the CR-transmit power.

The CR can also be an SU In this case, the LA used for spectrum prediction is unaffected by LCP when attempting to uphold the CPP. Assuming that β CEs execute prediction related to upholding the CPP, the CR's price of maintaining consciousness of the CR SU, Ω'' is:

$$\Omega'' = \sum_{u=1}^{s}(N_{LA}^{u}) + \left(\sum_{u=1}^{s-\beta}\left(1 - \frac{N_p^u}{N_T}\right)(\theta_u^v + \psi_u)\right) + \left(\sum_{u=1+(s-\beta)}^{s}(\theta_u^v + \psi_u)\right); N_p^u \leq N_T;\; u \neq v \tag{4.17}$$

In (4.17), the first term is the number of LAs in each CE. The second is the number of inter-CE and inter-LA connections active after LCP execution. The concerned LAs are not used for prediction related to upholding the CPP. The third is the number of active inter-CE and inter-LA connections between CEs and LAs. As an SU, the CR's transmission power is limited to uphold the CPP. Let ƚ be the reduction in the CR-transmit power. The CR-transmit power, P'' is:

$$P'' = \left(P + \mu(\Omega - \Omega'')\right)(1 - ƚ) \tag{4.18}$$

The CR-channel capacity is formulated for three scenarios, i.e. scenarios A_1, A_2, and A_3. Scenario A_1 considers the non-SU CR without LCP. This is the case with the existing scheme [90]. Scenario A_2 considers the CR non-SU with LCP. Scenario A_3 focuses on the CR SU with LCP. The CR transmit power on $c_{b'}$ in A_1, A_2 and A_3, are denoted $\left(P_{b'}^{A_1}\right), \left(P_{b'}^{A_2}\right)$ and $\left(P_{b'}^{A_3}\right)$, respectively. The CR has channel-bonding capacity. The CR-Th in A_1, A_2 and A_3 are $\left(Th_{A_1}\right), \left(Th_{A_2}\right)$ and $\left(Th_{A_3}\right)$, respectively. Th_{A_1}, Th_{A_2} and Th_{A_3} can be computed as:

$$Th_Y = \sum_{b'=1}^{b} B_{b'} \log_2\left(1 + \frac{P_{b'}^{Y}|h_{b';}^{t}|^2}{\left(\left|h_{b'}^{in}\right|^2 P_{b'}^{in}\right) + \sigma^2}\right) \;;\; Y \in \{A_1, A_2, A_3\} \tag{4.19}$$

$$\sum_{b'=1}^{b} P_{b'}^{A_1} \leq P \tag{4.20}$$

$$\sum_{b'=1}^{b} P_{b'}^{A_2} \leq P' \tag{4.21}$$

$$\sum_{b'=1}^{b} P_{b'}^{A_3} \leq P'' \tag{4.22}$$

4.5 Performance Evaluation

This section presents and discusses the simulation results for the proposed mechanism. It is divided into two parts. The first and second part presents the simulation results for LDS and LCP, respectively.

4.5.1 Learning Diversity Selection - Simulation and Discussion

The performance of the CR incorporating LDS is investigated using the parameters shown in Table 4-2.

Table 4-2: Learning diversiy selection - simulation parameters

S/N	Simulation Parameters	Values
1	Initial CR Battery Capacity	130mW
2	Number of LAs	10
3	Incoming CR Battery Power Expended in acquiring the training data from eNode B	4mW
4	Mean Battery Power expended in training each LA	6.85mW
5	Average training duration per LA	9.73ms
6	LTE-A MGL	6ms
7	LTE-A Measurement Gap-Repetition Period	40ms
8	Transmission Channel Gain	0.78
9	Average Interference-channel gain	0.45
10	Average Interference power	1.5mW

In the simulation, it is assumed that the best performing LA is selected to reduce PU-SU interference and enhance the QoS of the CR (SU). It focuses on the performance of LDS on one incoming CR. However, the performance simulation can be scaled to involve multiple incoming CRs, if incoming CRs do not interfere with each other. The performance benefit of the proposed LDS when incorporated in an incoming CR is conducted using the parameters in Table 4-1 via MATLAB. The performance of LDS is compared with that of a CR incorporating learning diversity, but without LDS. Such a CR is described in [90].The incoming CR transmission power is investigated as a function of the number of incoming CR's LAs; and the simulation results are shown in Figure 4-7.

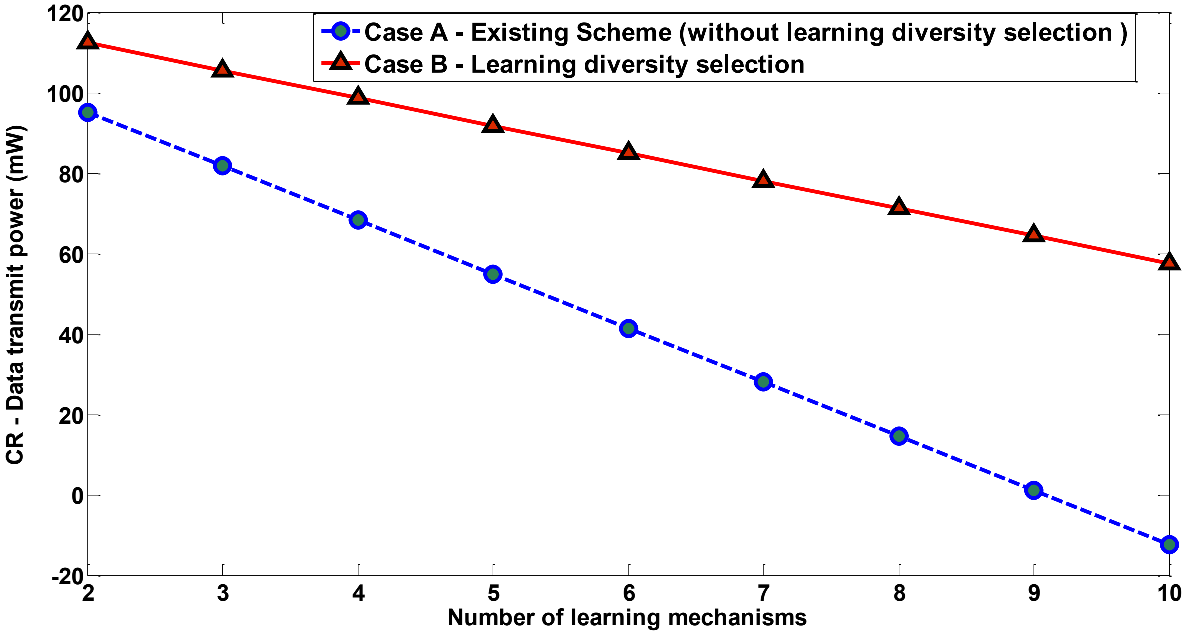

Figure 4-7: CR-transmit power with and without learning diversity selection.

From the results in Figure 4-7, it can be seen that the incorporation of more LAs in the incoming CR reduces the battery power. This is because the incoming CR expends more battery power in training multiple LAs in the absence of the proposed LDS. The incorporation of LDS also reduces the data transmission power with an increasing number of LAs. The results in Figure 4-7, shows that a negative incoming CR data-transmission power is obtained when the incoming CR does not use LDS. A negative value implies that the incoming CR battery power is expended during the LA training process. Therefore, the incoming CR needs to be recharged; and it cannot proceed to transmit data if the LA training is completed.

In the absence of LDS, incoming CR data transmission is not feasible when there are 9 and 10 LAs. LDS enables the incoming CR to transmit the data for a higher number of LAs. The incoming CR data-transmission power is positive when the incoming CR has 9 and 10 LAs. Therefore, LDS incorporation enables the incoming CR to have more transmission epochs.

Further investigations show that LDS enhances incoming CR data transmission power by an average of 48.2%. This computation has been done considering only cases, when the incoming CR data transmission power is positive. In addition, LDS enhances the number of transmission epochs by 51.8% on average.

The incoming CR data-transmission duration is also investigated and the performance results are shown in Figure 4-8. As shown in Figure 4-8, the incoming CR data-transmission duration reduces with the number of LAs. It is therefore assumed that the LA training duration increases when the incoming CR uses more LAs.

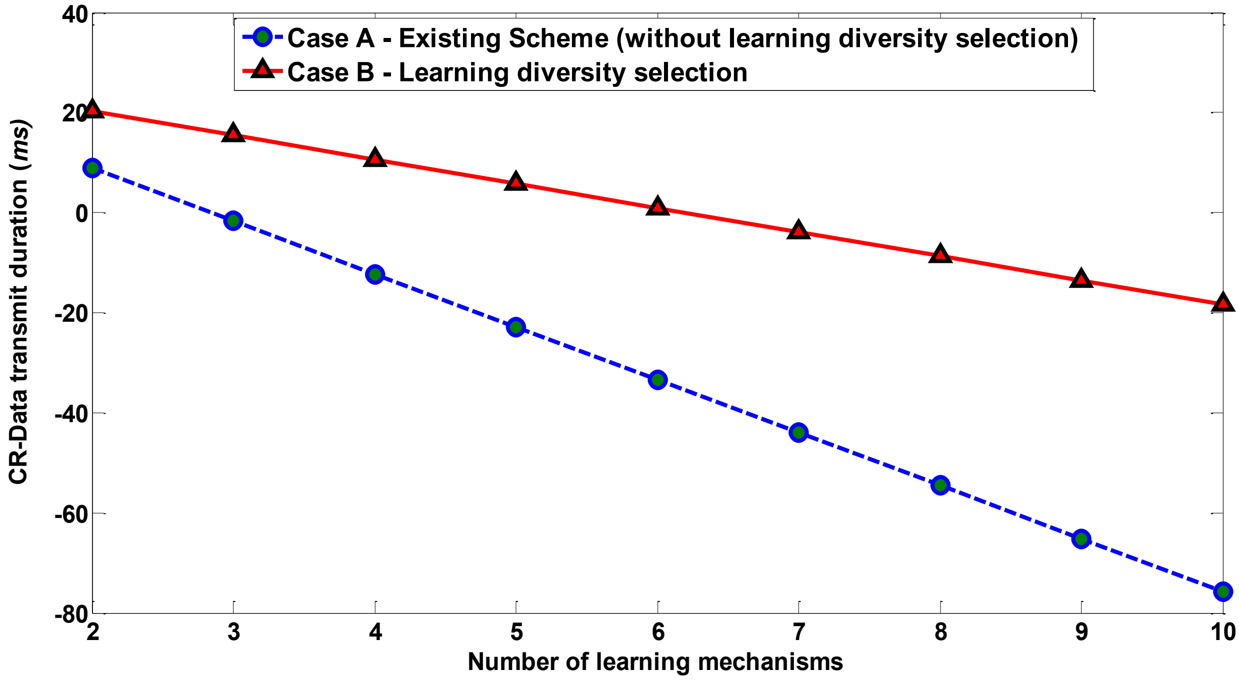

Figure 4-8: Cognitive radio transmit duration with and without learning diversity selection.

In the absence of LDS, the training of multiple LAs reduces the transmission duration of CRs in LTE-A. This is because a negative transmission duration is obtained over more epochs, when the LDS is not incorporated. A positive data-transmission duration is obtained when the incoming CR without LDS has 2 LAs. The incorporation of LDS increases CR transmission epochs. The CR can transmit, when the CR has 2, 3, 4, 5 and 6 LAs. Therefore, LDS enhances the CR data transmission.

Further investigations show that LDS incorporation in the CR enhances transmit duration by 56.4%. This computation has been done considering only the positive values of the data-transmission duration obtained in the simulation. The incoming CR throughput (CR-Th) is examined; and the performance simulation results are shown in Figure 4-9. The achieved incoming CR throughput when there are 9 and 10 LAs are infeasible since incoming CR data transmit power is negative. As shown in Figure 4-9, the incoming CR throughput reduces with an increasing number of LAs. This is because the incoming CR data-transmission power reduces with the number of LAs used by the incoming CR.

In the absence of LDS, there is an unexpected increase in the throughput, when there are 10 LAs. However, it is noted that the incoming CR transmission power is negative in this case. Therefore, incoming CR data transmission is not feasible; and this case is not considered further in the discussion. When the proposed LDS is incorporated, it is observed that the throughput reduces with an increasing number of LAs. Further investigations shows that LDS incorporation enhances incoming CR throughput by 22.7% on average.

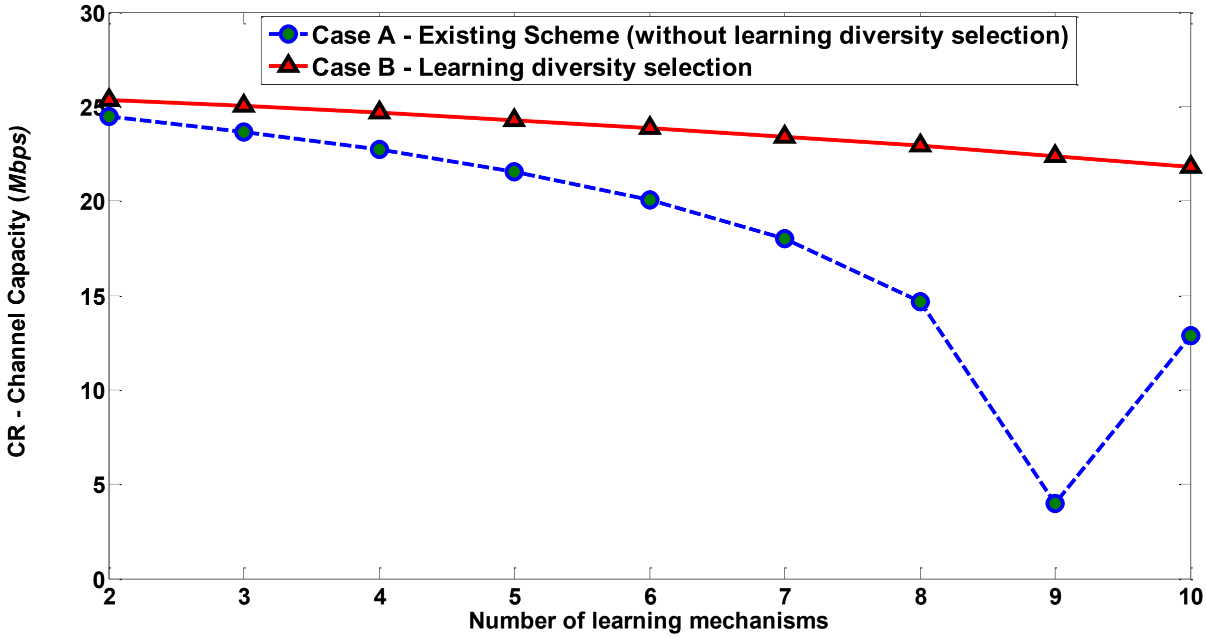

Figure 4-9: Cognitive radio channel capacity with and without learning diversity selection.

We also investigated the amount of data that can be transmitted by the incoming CR; and the result is shown in Figure 4-10. The achieved incoming CR data transmitted when there are 9 and 10 LAs are infeasible since incoming CR data transmit power is negative. As shown in Figure 4-10, the incorporation of LDS enables the incoming CR to transmit more data on a channel. In Figure 4-10, a positive value of the transmitted data implies that the incoming CR can transmit data without switching channels. A negative value of the transmitted data implies that the incoming CR cannot transmit data. In this case the CR needs to switch channels. LDS incorporation enables the CR to transmit data over more epochs, compared to when the CR does not incorporate LDS. This is because more positive transmitted data values are obtained when the incoming CR uses LDS. Hence, LDS enhances incoming CR throughput, transmission power, transmission duration and transmitted data. This is because the CR obtains more positive values of the data transmission duration when LDS is incorporated.

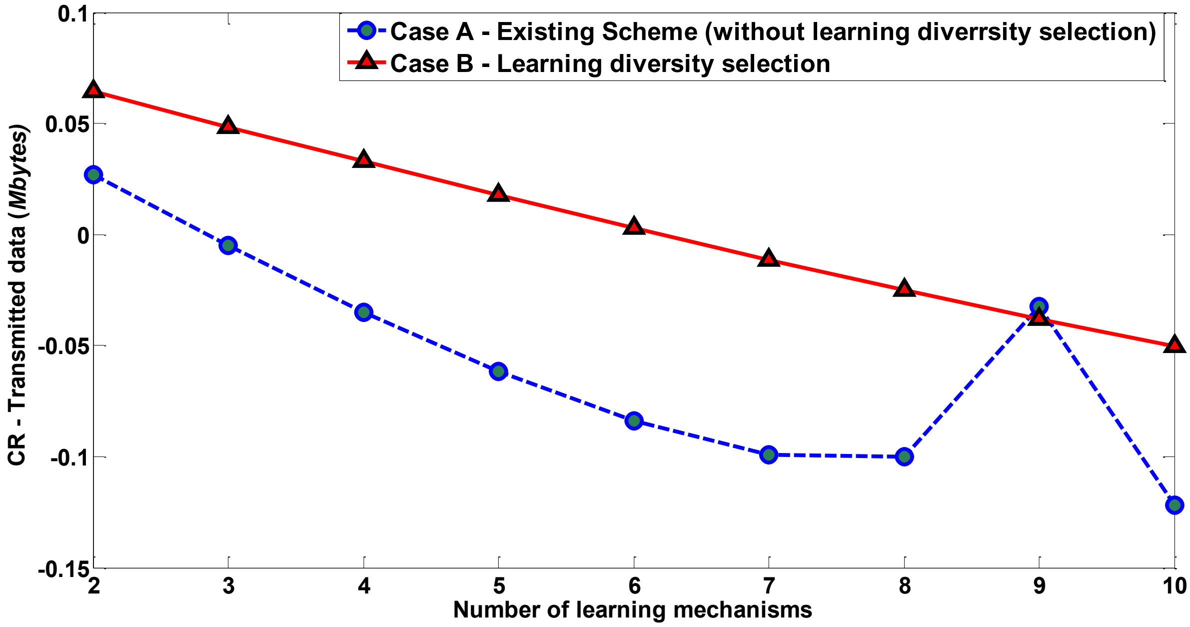

Figure 4-10: Cognitive radio transmitted bytes with and without learning diversity selection.

4.5.2 LA Classification Pause – Simulation and Discussion

The performance of the CR incorporating LCP is investigated, using the parameters in Table 4-3.

Table 4-3: Learning classification pause simulation parameters

Parameter	Value
Communication Path Model Parameters	
Number of paths	6
Number of sub-paths	20
Number of antenna elements in eNB	6
Number of antenna elements in CR	6
Mean Inter-element distance in eNB	20.8cm
Mean Inter-element distance in CR	19.3mm
CR Speed	16.7m/s
Orientation of eNB with respect to the CR	60 deg
Cognitive Radio-Power Reduction Ratio	0.65
Cognitive Engine Configuration	
Initial CR battery power (mW)	25
Power consumed per CE classification (mW)	4.7
Vector of Number of CEs in CRs	[1 2 3 4 5 6 7 8]
Number of LAs in each CE	6
Number of connections between first 3 CEs	1
Number of connections between last 5 CEs	Zero
Number of Decision-Making Layers in first 3 CEs	2
Number of Decision-Making Layers in Fourth CE	1
Number of CEs used for spectrum prediction	2
Number of LAs in spectrum prediction CEs	6
Number of Decision Layers per CE (Last 4 CEs)	2
Pause Efficiency of CEs used in spectrum prediction (after spectrum prediction)	100%
Pause Efficiency	25%
Pause-Transfer Efficiency	4.50%

The CR's price of maintaining consciousness is simulated by using the parameters in Table 4-3 for three scenarios. The first scenario is A_1 where there is a PU CR without LCP. The second is A_2 where the PU CR incorporates LCP. The third is A_3 where the SU CR incorporates LCP. The result is shown in Figure 4-11. As shown in Figure 4-11, the CR has the highest number of CR-PMCs in A_1 compared to cases A_2 and A_3. Case A_2's CR's price of maintaining consciousness is lower than that of case C's CR's price of maintaining consciousness, by 12% on average. In addition, case A_3's CR's price of maintaining consciousness is lower than case A_1's CR's price of maintaining consciousness, by 7.6% on average. The CR SU has a higher CR's price of maintaining consciousness because of the additional LAs in the CEs used for CR spectrum prediction.

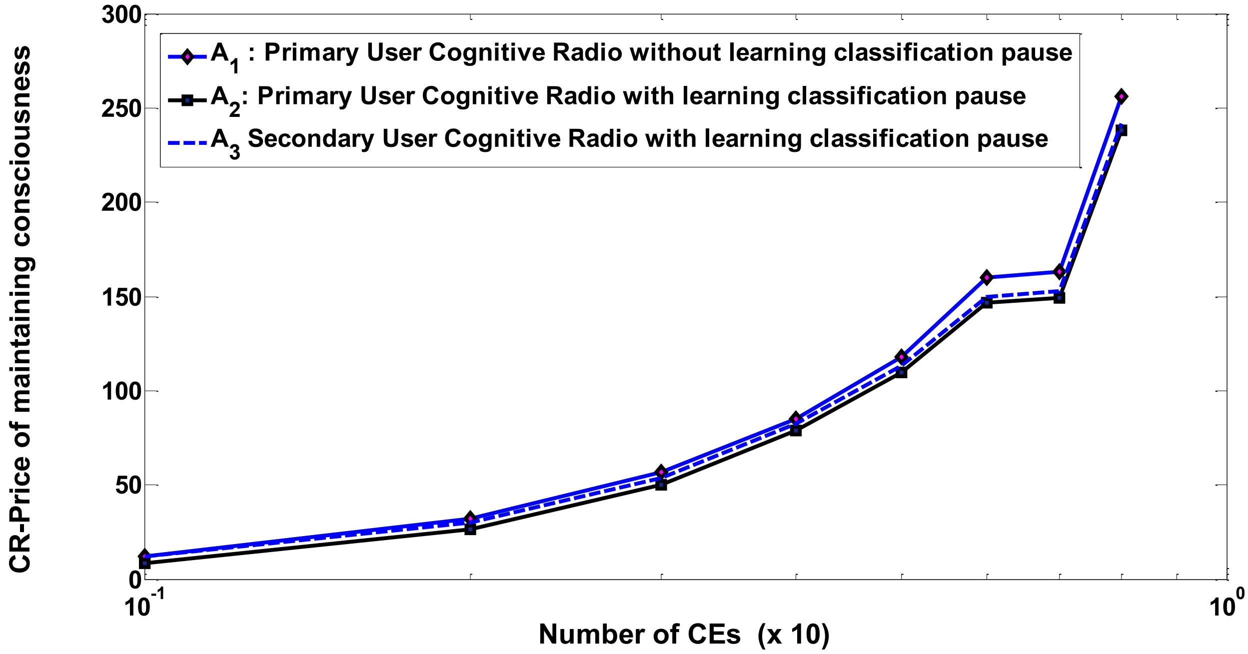

Figure 4-11: The cognitive radio price of maintaining consciousness as a function of the number of cognition engines.

The CR-transmit power is investigated; and the result is shown in Figure 4-12. As shown in Figure 4-12, the addition of more CEs reduces the CR-transmit power. The addition of more CEs increases the CR's battery power expended on LA classification. It is also observed that CR-transmit power is negative when the CR has 6, 7 and 8 CEs. A negative CR-transmit power implies that the CR battery power is expended.

The improvement in CR-transmit power of the proposed framework is examined for the cases where the CR-transmit power is positive. The CR-transmit power is positive for cases A_1, A_2 and A_3, when the CR has 1, 2, 3, 4 and 5 CEs. Scenario A_2's CR-transmit power exceeds scenario A_1's CR-transmit power by 80% on average. This is because in A_2, the CR uses LCP and does not limit the CR-transmit power. The CR-transmit power is not limited in A_2; since the CR is not an SU.

The CR-transmit power in A_3 is also reduced to reduce in-band and out-band interference. In A_3, the CR-transmit power exceeds that of scenario A_1 by 65% on average. Although, the CR-transmit power is reduced in A_3, a higher CR-transmit power is obtained in A_3 than in A_1. The improvement in CR-transmit power in A_3 is obtained because the CR incorporates LCP. A_3 's CR-transmit power is lower than the CR-transmit power in A_1 and A_2, when the CR has only one CE. In this case, LA classification is not paused because the CR is a SU; and it must have reduced in-band and out-band interference.

For A_2 and A_3, the CR-transmit power increases for the first three CEs; and it then decreases when the CR has up to four CEs. This is because the fourth CE has only one DML. Therefore, LCP saves CR battery power.

In A_2 and A_3, the CR-transmit power increases when the CR has between 5 and 8 CEs. In this case, the CEs have the same number of layers. Therefore, the CR-transmit power is enhanced when CEs have a uniform number of layers, compared to when the number of layers is non-uniform. The CR-transmit power is positive for all CEs in scenarios A_2 and A_3. In the absence of LCP, the CR cannot transmit, when the CR has more than five CEs (negative CR-transmit power).

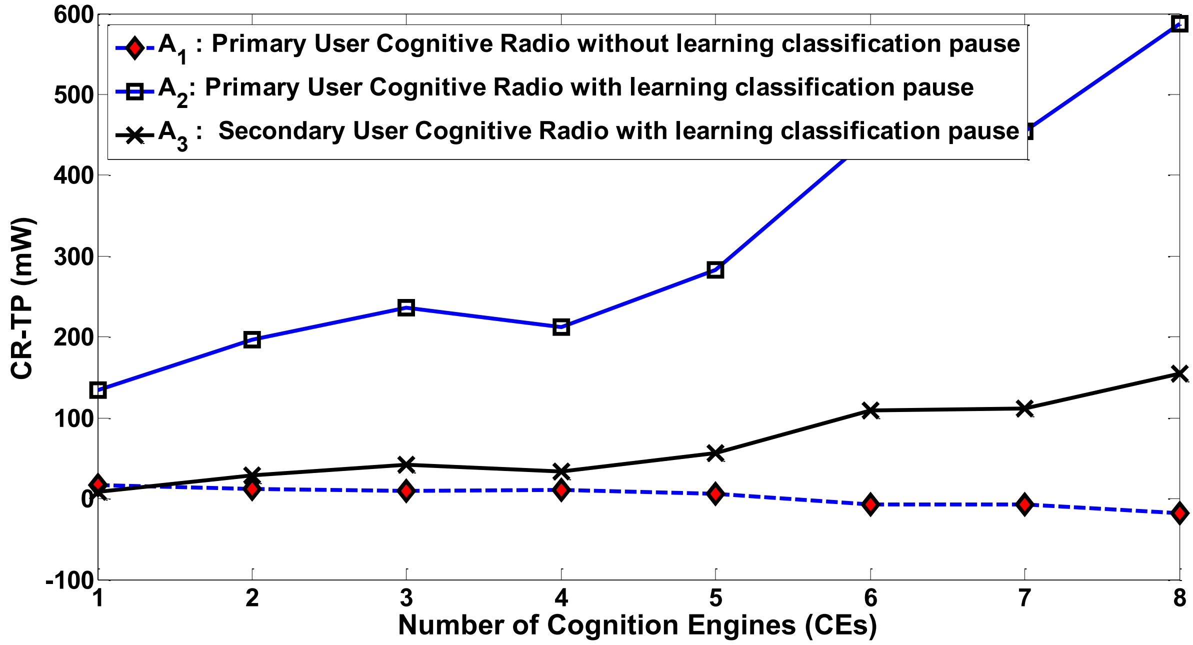

Figure 4-12: Cognitive radio trasnsmit power as a function of the number of cognition engines.

The CR channel capacity is also investigated for scenarios A_1 , A_2 and A_3, as shown in Figure 4-13. The CR-channel capacity is decreasing in A_2 because of the decreasing CR-transmit power, when the CR has more CEs. The CR does not transmit data when the CR-transmit power is negative. The CR-channel capacity in A_2 outperforms that of A_3, when the CR has one CE. When the CR has only one CE, the minimum CR-channel capacity is that of A_3, when compared to A_1 and A_2. Given that the CR has one CE, the CR-transmit power is at a minimum in A_3, when compared with A_1 and A_2. This is due to the necessity of completing the LA classification.

The CR-channel capacity is at a maximum in A_2, when the CR's CEs are more than one. In A_2, LCP is incorporated in the CR. Furthermore, the CR-transmit power is not reduced; because the CR is not an SU. Hence, the CR-channel capacity in A_2 exceeds that of A_3. The CR-channel capacity in A_2 exceeds that of A_1; due to LCP incorporated in the CR in A_2. The CR-channel capacity in A_1 is observed to be at a minimum when the CR has between 2-5 CEs. The CR-channel capacity in A_2 exceeds that of A_1 by 80% on average. The CR-Th in A_3 exceeds A_1 by 23% on average. The reduction of the CR-transmit power, when the CR is a SU reduces the CR-channel capacity by 57% on average.

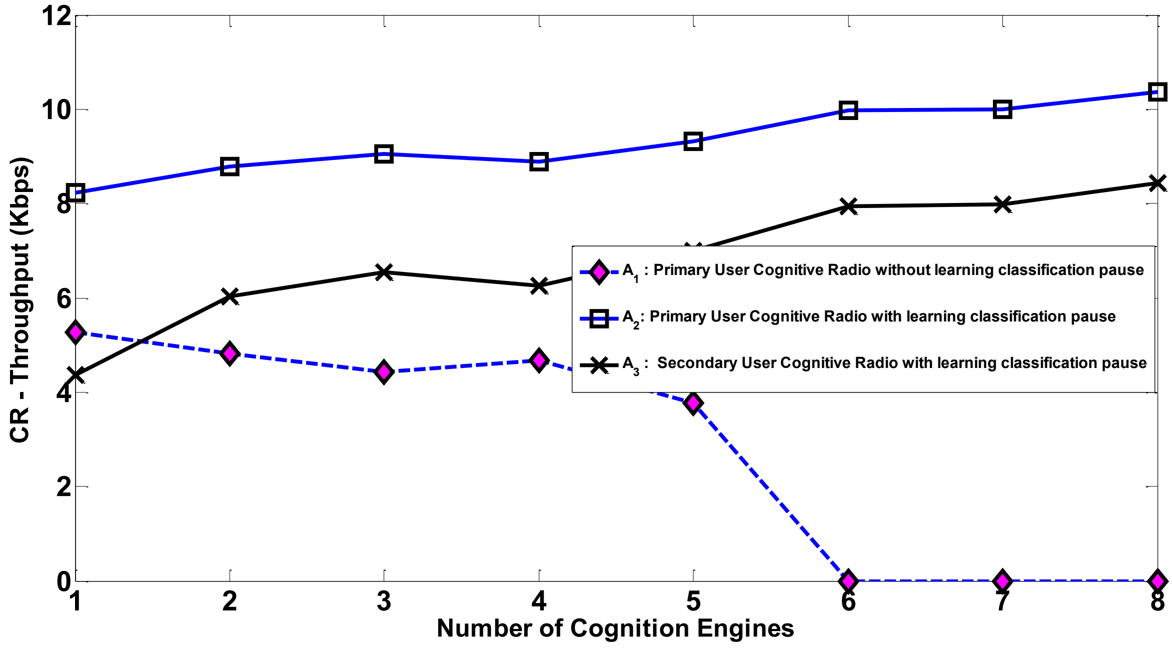

Figure 4-13: Cognitive radio channel capacity as a function of number of cognition engines.

We also investigate how varying the power transfer efficiency, μ and the number of paused CEs affects CR-channel capacity. The results of investigating the trade-off between μ, CR-channel capacity and the number of paused CEs is shown in Figure 4-14. It can be seen that CR-channel capacity increases with the number of paused CEs. The CR-channel capacity is improved by 4.5% on average, when the number of paused CEs increases from two to four. Increasing the number of paused CEs from 2 to 6 improves the CR-channel capacity by 19.6%. Furthermore, a fourfold increase of CEs from 2 to 8 enhances the CR-channel capacity.

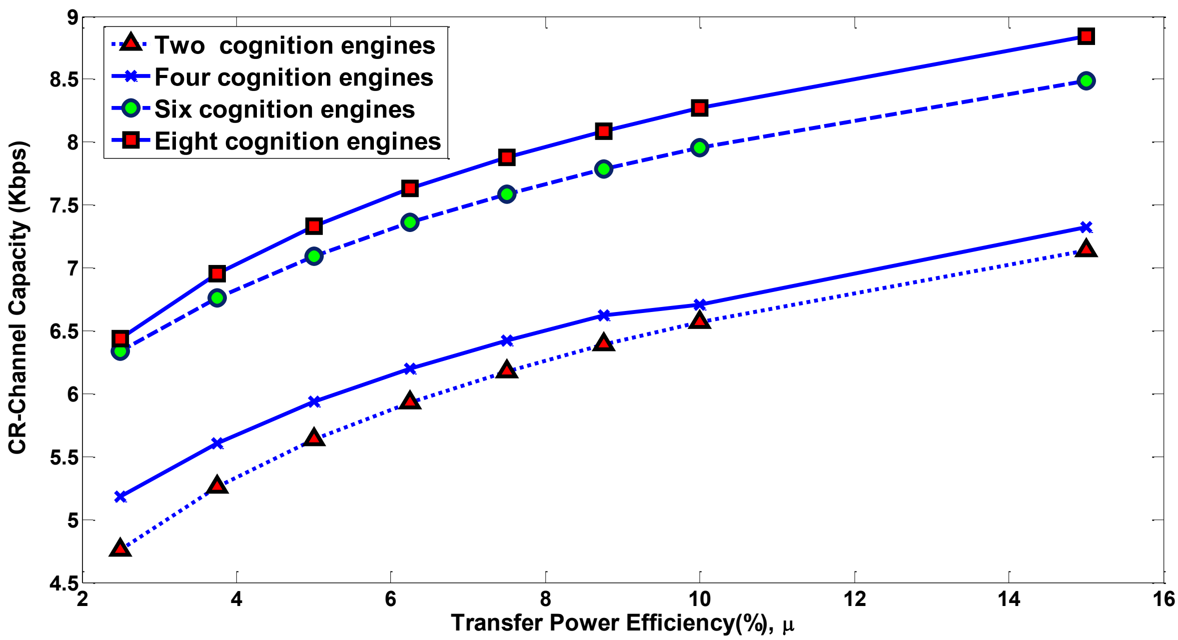

Figure 4-14: Analysis showing throughput and transfer power efficiency

An increase in the number of paused CEs enhances the CR-channel capacity. The CR-channel capacity is enhanced by 5.9% on average, when the paused CEs are increased from 2 to 4. A threefold increase in the number of paused CEs from 2 to 6 enhances the throughput by 21.8% on average. The CR-channel capacity is enhanced by 24% when paused CEs are increased from 2 to 8. A similar analysis is also performed for group 2. The CR-channel capacity improves by 3%, 17.4% and 20.6%, respectively, when paused CEs increase from 2 to 4, 6, and 8, respectively. The CR-Th is more enhanced in group 1 than in group 2. In groups 1 and 2, the maximum μ is two-fifths and twice the minimum of μ, respectively.

4.6 Conclusion

This chapter proposes a mechanism that enhances the QoS of CRs with learning diversity. The CR uses learning diversity selection (LDS) and LA pause classification (LCP) to improve its QoS. This enables the CRs to meet the goals of the unified-application framework. The incorporation of LDS and LCP enable the CR to achieve an improved CR QoS. This is because LCP and LDS enable the CR to obtain an enhanced data-transmit power and throughput. The data-transmission power and throughput are enhanced without increasing the signalling overhead.

LDS enables the CR to devote battery resources to data transmission. This enhances the use of the LTE-A spectral resource in the RRC_CONNECTED DTT by training the best LA at the epoch. In LCP, CR resources are also re-directed towards CR data transmission. Similarly, spectral resources that could have been held by the CR in LTE-A TWN are made available for other technologies. The paused classification is completed at epochs when the CR no longer desires to transmit data.

Chapters 3 and 4 have focused on designing algorithms that can realise the goals of the unified-application framework in TWNs. The achieved goals are those of enhancing CR QoS by incorporating enhanced cognition mechanisms. The next chapter considers relations between TRAOs, ISLs and TWNs.

Chapter 5

Optimisation Mechanism for Terrestrial Radio Astronomy Observations

This chapter proposes a mechanism that optimises the conduct of terrestrial radio astronomy observations (TRAOs). The proposed mechanism optimises TRAOs by using the CR paradigm (CRP) to achieve three objectives for TRAOs. The first and second objectives are reducing GBTs-ISL interference and improving HPC utilisation, respectively. The third objective is enhancing angular resolution. The TRAO user is the terrestrial radio astronomy organisation.

The chapter is divided into six parts. The first part discusses related work. The second and third describes the problem and presents the proposed mechanisms, respectively. The fourth and fifth formulates the performance of the proposed mechanisms and presents evaluation results, respectively. The sixth is the conclusion.

5.1 Related Work

The discussion on TRAOs in this section is divided into two parts. The first part describes the spectrum access relations between radio astronomy observations and wireless communications. The second part discusses the evolution and types of radio-astronomy organisations.

5.1.1 Radio Astronomy and Wireless Communications

Radio spectrum is very important for service delivery in TWNs and CEOs, however, aside from TWNs and CEO, TRAOs also require spectrum access. TRAOs collect AS radio signals that are subsequently analysed by the HPC. Generally, radio astronomy observations can be conducted as TRAOs or space-radio astronomy observations. TRAOs use GBTs to receive ASs signals whereas space-radio astronomy observations use satellite astronomy payload to receive ASs signals [96].

TRAOs require bandwidth access to observe ASs via different SWs and are susceptible to interference from satellites. This is because the ASs have peak radiation at different SWs. Furthermore, TRAOs are affected by the blue shift and redshift effects that cause wavelength decrease and increase, respectively. GBTs require access to large bandwidth to observe different ASs, whose spectral lines are susceptible to blueshift and redshift.

In space radio astronomy observations, the transmitter is the space telescope with controllable-transmission parameters. For example, the polarisation of the space telescope and HPC antenna can be chosen to reduce interference with ISLs. In addition, the spectrum used for space telescope-HPC communications can be chosen to differ from the spectrum used by satellite applications. These options are available; since the space telescope's parameters are configurable. However, TRAOs do not have a similar configurable component in space. Therefore, TRAOs are more susceptible to interference than SRAOs.

An example of an interference source to the GBT is the ISL in global coverage LEO satellite constellations. Therefore, interference-reduction mechanisms are required to reduce interference between ISLs and GBTs used in TRAOs. A joint use of TRQZs and space radio quiet zones reduces the interference of GBTs. However, establishing space radio quiet zones has the following challenges:

1) **Unknown Signal-Propagation Paths:** The location of space radio quiet zones that protect TRAOs from interference assume that AS's radio waves have a known propagation path. However, this requires further investigation; because AS's radio waves can experience diffraction or reflection, when they hit GEO and LEO satellites.
2) **Orbital Re-design:** The establishment of space radio quiet zones requires orbital prioritization. Satellite orbits would need to be re-designed to consider low interference with AS's radio signals. This requires satellite-orbit design paradigms; and it is outside the scope of this thesis.

The focus of this chapter is the design of interference-reduction mechanisms for TRAOs using a CR spectrum-sharing model. Interference-reduction methods for TRAOs can be regulatory or technical [97]. The establishment of TRQZs to is an example of a strategy in the regulatory method. The challenge of reducing interference experienced by TRAO also extends to higher bands [98]. The CRP supports different spectrum-sharing models that can be used to design technical interference-reduction methods. Examples of the spectrum-sharing models supported by the CRP that can be used in TWNs are the underlay and interweave spectrum-sharing models. The use of SDRs for TRAOs has already been considered in [77]. However, [77] has not examined the spectrum-sharing capabilities of the CR.

The suitability of the underlying model for low interference co-existence between TRAOs and TWNs services is investigated in [13]. In the underlay model, spectrum-sharing between TRAOs and TWNs is achieved by constraining the transmit power. The analysis in [13] deems spectrum sharing between TWNs and ASs as infeasible; because ASs have a lower-radiated power than have TWNs.

AS radiated power is non-configurable and measured in milli-Jansky(mJy), $1\,Jy\ = 1\,x10^{-32}\,Wm^{-2}Hz^{-2}$ [36]. The reduction of mobile phone signal ($1\,x10^{12}\,Jy$ [36]) to milli-Jansky makes data-transmission challenging. Hence, [13] concludes that spectrum sharing between TWNs and TRAOs is not feasible. However, [13] has not considered the interweave model [3, 48]. The interweave model enables spectrum sharing by using patterns in the spectrum usage data of concerned applications. Therefore, spectrum-sharing mechanisms based on this model are desirable.

5.1.2 Terrestrial Radio-Astronomy Organisations

The emergence of different astronomical organisations that conduct TRAOs is recognised in [14-15]. Some terrestrial-radio astronomy organisations use GBTs realised by the conversion of unused satellite-earth stations [73-76]. It is assumed that GBTs realised from this conversion will be used in a TRQZ. However, TRQZs are becoming scarce due to the increasing proliferation of broadband TWNs. Hence, TWN presence in the destination-radio environment i.e. the intended TRQZ should be considered [34, 36-37]. Terrestrial radio astronomy organisations that use converted GBTs require reduced ISL interference and enhanced angular resolution. In addition, terrestrial-radio astronomy organisations also aim to enhance HPC utilisation.

HPC underutilisation limits HPC power efficiency (PE) and arises because of observation limitation conditions [15]. Observation limitations arise due to GBT maintenance and limiting weather conditions. These factors reduce the number of GBTs presenting data to the HPC. Barbosa *et al*. [15] propose the use of time multiplexing to share the HPC with other applications that use the HPC's idle capacity. However, time multiplexing does not address low-resource utilisation that occurs in a time slot. A mechanism that enhances HPC utilisation and considers the under-utilisation that arises in time slots is required. The following observations can be made for TRAOs:

1) **Observation Goals:** The siting of ideal TRQZs for TRAOs is challenging, due to ISL interference and TWN proliferation in high-population density areas [36-37]. TWN presence degrades TRAO angular resolution. The angular resolution is degraded because the TWN radiation pattern infiltrates the signal received by GBTs.
2) **HPC Utilisation:** HPC utilisation is important; and time-multiplexing has been proposed to enhance HPC utilisation. This shows that there is the potential to improve TRAOs by creating a platform for interaction with other technologies. The synergy enhances these technologies and improves TRAOs.

5.2 Problem Description

This section describes the problem being addressed in this chapter and uses the parameters in Table 5-1.

Table 5-1: Parameters used in problem formulation.

F	Set of Radio Frequencies for ISL transmission and GBT observation.
S	Set of ISLs used by LEO satellites.
Φ	Set of GBTs.
s_1^f	ISL l_1 using f.
ϕ_a^f	GBT used for terrestrial radio astronomy observation (TRAO) over sky region a using f.
X	Entity X, X could be either S or ϕ
I_X^f	Spectrum usage indicator of X
$\phi_1^{f_1}$	GBT $\phi_1$using frequency f_1 for TRAOs, $f_1 \epsilon f$.
$I(\Upsilon)$	Indicator signifying that GBT can or cannot meet Υ
$I(L)$	TWN indicator indicating absence or presence of L in GBT vicinity
τ	Set of duty cycle of high performance computing infrastructure (HPC) at instant t.
τ_{thr}	Threshold HPC duty cycle.
$ð_1$	Angular resolution when only converted GBTs are used for TRAOs in absence of TWNs.
$ð_2$	Angular resolution when GBTs and MESs are used for TRAOs in absence of TWNs.
$ð_3$	Angular resolution when MESs and GBTs are used for TRAOs; there is TWN interference.
$ð_4$	Angular resolution when MESs and GBTs are used in presence of TWNs with interference reduction.
Sc	Probability of having sufficient HPC resources
Sa	Probability of functional computing module in HPC.
Sp	Probability of using HPC to train cognitive TWN algorithms.

TRAOs is susceptible to interference from LEO satellites constellations that use intersatellite links (ISLs). ISLs pose interference threats to GBTs when their transmit epoch coincides with GBT observation epoch. The radiated ISL signal has a higher power than the AS's signal received by the GBT. ISL interference can also cause subtle distortions to AS data [69]. Hence, the ISL signals pose interference risks to TRAOs.

The scenario being considered comprises LEO constellation satellites with ISLs, GBTs and ASs in a TRQZ. Let (F) be the set of radio frequencies that can be used by ISLs for data transmission or GBTs for TRAOs. The set of ISLs and GBTs are given as (S) and (ϕ), respectively. F, S and ϕ can be given as:

$$F = \{f_1, \dots, f_n\} \tag{5.1}$$

$$S = \{s_1^f, \dots, s_n^f\}, f \epsilon F \tag{5.2}$$

$$\phi = \{\phi_1^f, \dots, \phi_a^f\}, f \epsilon F \tag{5.3}$$

Multiple ISLs can exist over the GBT TRQZ coverage area. In addition, a given ISL can span multiple TRQZ coverage areas. Hence, the number of GBTs and ISLs using a frequency are not necessarily equal.

Let $I_X^f \epsilon \{0,1\}, X \epsilon \{S \cup \phi\}$ be the spectrum usage indicator of X on f; $f \epsilon F$. $I_X^f = 0$ and $I_X^f = 1$ indicate that X is inactive and active in f, respectively. If ISLs transmission and GBTs observation are in the same sky region, interference occurs if $I_{s_c^f}^f = 1$; $(s_c^f \epsilon S)$ when $I_{\phi_b^f}^f = 1$; $(\phi_b^f \epsilon \phi)$. It is desired that $I_{s_c^f}^f = 0$ when $I_{\phi_b^f}^f = 1$.

The case $I_{s_c^f}^f = 1$ when $I_{\phi_b^f}^f = 0$ is also plausible. In this case, interference reduction requires that the LEO satellite sends information on ISL transmission epoch to the terrestrial radio astronomy organisation. This transmission increases satellite overhead because it uses satellite resources for purposes other than data transmission.

Furthermore, let $I(\Upsilon) \epsilon \{0,1\}$ and $I(L) \epsilon \{0,1\}$ be the TRAO objective indicator and TWN indicator, respectively. $I(\Upsilon) = 0$ and $I(\Upsilon) = 1$ signifies that available GBTs cannot and can satisfy the observation objective at enhanced angular resolution, respectively. $I(L) = 0$ and $I(L) = 1$ denote TWN absence and presence in GBTs vicinity, respectively. In the scenario, $I(\Upsilon) = 0, I(L) = 1$, the terrestrial astronomy organisation cannot satisfy its observation objectives at enhanced angular resolution due to TWN interference. The terrestrial radio astronomy organisation can meet its observation objective at enhanced angular resolution and does not experience TWN interference when $I(\Upsilon) = 1, I(L) = 0$.

The realisation of TRAO objectives at enhanced angular resolution is threatened by TWN interference when $I(\Upsilon) = 1, I(L) = 1$. The terrestrial radio astronomy organisation needs access to additional GBTs to improve its angular resolution when $I(\Upsilon) = 0, I(L) = 0$. The proposal in this chapter aims to enhance the angular resolution when $(I(\Upsilon) = 0, I(L) = 1)$, $(I(\Upsilon) = 1, I(L) = 1)$ and $I\big((\Upsilon) = 0, I(L) = 0\big)$.

In the second problem considered in this chapter, the focus is on enhancing HPC utilisation. The AS data received by the GBT is processed at the HPC at different time epochs. The terrestrial radio astronomy organisation seeks to maximize HPC utilisation. Let $\tau = \{\tau_1, \dots, \tau_q\}$ denote the set of HPC duty cycle. In addition, let τ_{thr} denote the HPC threshold duty cycle. HPC underutilisation occurs when $\tau < \tau_{thr}$. The second problem addressed in this chapter is enhancing HPC utilisation.

5.3 Proposed Mechanism

This section presents solutions that enable the proposed mechanism to achieve three objectives. These objectives are interference reduction from ISLs, enhancing angular resolution and improving HPC utilisation. They are achieved for a terrestrial radio astronomy organisation. It is divided into three parts. The first part addresses the objective of reducing GBTs-ISL interference. The second focuses on improving the angular resolution. The third aims to realise the objective of enhancing HPC utilisation.

5.3.1 Terrestrial Radio Astronomy Organisation - Interference-Reduction

A spectrum sharing model is developed to prevent ISLs from interfering with GBTs. In this model ISLs and GBTs are the SUs and PUs , respectively. Interference is reduced by allowing ISLs (SUs) to transmit when PUs (GBTs) are inactive. This objective is achieved by sending the TRAO observation program to LEO satellites. The TRAO sends its observation plan (OBL) and astronomy spectrum database (ASD) to the satellite. The satellites processes the OBL and the ASD using its cognitive reasoner (CRE) and the cognitive satellite ISL activator/deactivator (CSLA). Communication between TRAO and the satellite are realised through the plan-acquisition channel (PAC).

The OBL is generated on ground by the astronomy organisation; and it comprises information on the TRAO survey area, the ASs and the desired observation frequencies. It is known *a priori* to the astronomical organisation. The ASD is an aggregate of multiple OBLs that is transmitted to in-orbit satellites via the PAC.

The CRE and CSLA process the received ASD. The CRE analyses the ASD and determines AS observation epochs and duration. It uses these outputs to determine satellites from which the ISLs are to be deactivated and the deactivation duration. The CRE's functions are executed by the receiving satellite and sent to other satellites via ISLs lying outside the TRAO vicinity. The receiving satellites have their own CRE and CSLA. The CSLA is used to deactivate the ISLs for the duration determined by the CRE. The concerned ISLs are deactivated for a given duration, in order to observe ASs. The CRE processes the ASD that is pre-complied during the data aggregation. It determines the AS observation duration and the epoch from the received ASD.

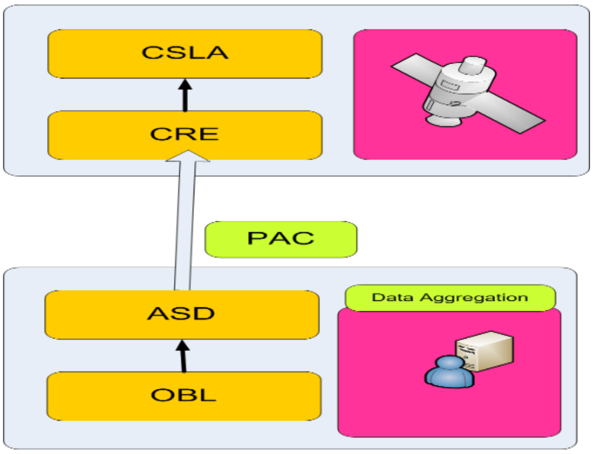

Figure 5-1: Interaction between entities involved in interference reduction.

A sample ASD that is processed by the CRE is obtained from the KAT-7 observation data, and is shown in Figure 5-2. The sample ASD shows information for astronomy source observation conducted on Feb 16th 2013. The columns of interest are the first and third columns. The first column holds information on the period spent receiving AS radio signal. The third column holds name of AS.

16-Feb-2013/08:42:05.3 - 08:56:45.3	1	0 PKS 1934-638	1869	10	[0]
08:57:45.3 - 09:12:25.4	2	1 PKS J0010-4153	1869	10	[0]
09:13:15.4 - 09:27:55.4	3	2 PKS J0022+0014	1869	10	[0]
09:28:45.4 - 09:43:35.4	4	3 PKS J0024-4202	1890	10	[0]
09:44:05.4 - 09:58:45.4	5	4 PKS J0025-2602	1869	10	[0]
09:59:35.4 - 10:14:15.4	6	5 PKS J0042-4414	1869	10	[0]
10:14:45.4 - 10:29:25.4	7	6 PKS J0044-3530	1869	10	[0]
10:30:15.4 - 10:44:55.4	8	7 PKS J0059+0006	1869	10	[0]
10:45:35.4 - 11:00:15.4	9	8 3C348	1869	10	[0]
11:01:05.5 - 11:15:45.5	10	9 PKS J0240-2309	1869	10	[0]
11:16:45.5 - 11:31:25.5	11	10 PKS J0252-7104	1869	10	[0]
11:31:55.5 - 11:46:35.5	12	11 PKS J0303-6211	1869	10	[0]
11:47:05.5 - 12:01:45.5	13	12 PKS J0309-6058	1869	10	[0]
12:02:55.5 - 12:17:35.5	14	13 PKS J0318+1628	1869	10	[0]
12:18:15.5 - 12:32:55.5	15	14 PKS J0323+0534	1869	10	[0]
12:33:35.5 - 12:48:15.5	16	15 PKS J0351-2744	1869	10	[0]
12:48:55.5 - 13:03:35.6	17	16 PKS J0405-1308	1869	10	[0]
13:04:05.6 - 13:18:45.6	18	17 PKS J0409-1757	1869	10	[0]
13:19:45.6 - 13:34:25.6	19	18 3C123	1869	10	[0]
13:35:45.6 - 13:50:35.6	20	19 PKS J0408-6544	1890	10	[0]
13:51:05.6 - 14:05:45.6	21	20 PKS J0420-6223	1869	10	[0]
14:06:25.6 - 14:21:05.6	22	21 PKS J0440-4333	1869	10	[0]
14:22:05.6 - 14:36:45.6	23	22 PKS J0442-0017	1869	10	[0]
14:37:25.6 - 14:52:05.6	24	23 PKS J0444-2809	1869	10	[0]
14:52:35.6 - 15:07:15.7	25	24 PKS J0453-2807	1869	10	[0]
15:08:05.7 - 15:22:45.7	26	25 PKS J0519-4546	1869	10	[0]
15:23:55.7 - 15:38:35.7	27	26 PKS J0534+1927	1869	10	[0]
15:39:35.7 - 15:54:15.7	28	27 PKS J0538-4405	1869	10	[0]
15:55:05.7 - 16:09:45.7	29	28 PKS J0635-7516	1869	10	[0]
16:10:55.7 - 16:25:35.7	30	29 PKS J0744-0629	1869	10	[0]
16:26:15.7 - 16:40:55.7	31	30 PKS J0837-1951	1869	10	[0]

Figure 5-2: Sample observation plan processed into the astronomy spectrum database.

5.3.2. Terrestrial Radio Astronomy Organisation - Enhancing Angular Resolution

The thesis proposes an algorithm to enhance the TRAO angular resolution by using CRs to design multi-mode earth stations (MESs). The MESs is an earth station that can be used for satellite communications and TRAOs, such as the Goonhilly-3 GBT [73]. However, the Goonhilly-3 GBT does not use the CR for switching between TRAOs and satellite communications. An opportunistic use of MESs enhances the angular resolution when using the MES increases number of telescopes and telescope separation.

In the case where the converted GBTs are in the vicinity of TWNs, the TWNs interfere with the TRAO signals. The interference reduces the influence of the telescope separation i.e. baseline in enhancing the angular resolution. Each converted GBT has a virtual-radio environment multiple converted GBTs have a large-sized virtual environment. In a large virtual radio environment, more details can be obtained from multiple-observation sky regions. The low interference virtual radio environment of three GBTs is shown in Figure 5-3.

An high virtual-radio environment radius signifies that the SW of converted GBTs has a low susceptibility to interference over a large sky region. The presence of the TWN in the destination environment reduces the virtual-radio environment radius perceived by the converted GBT.

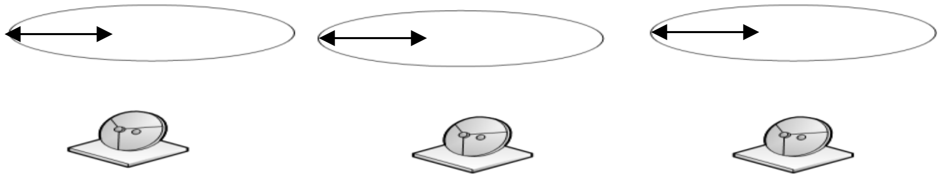

Figure 5-3:Low interference virtual radio environment of converted ground based telescopes

A scenario showing how TWN interference of TWNs affects the virtual-radio environment radius is presented in Figure 5-4. In Figure 5-4, the TWN's virtual radio environment overlaps with the virtual radio environment of the first two GBTs (from the left).

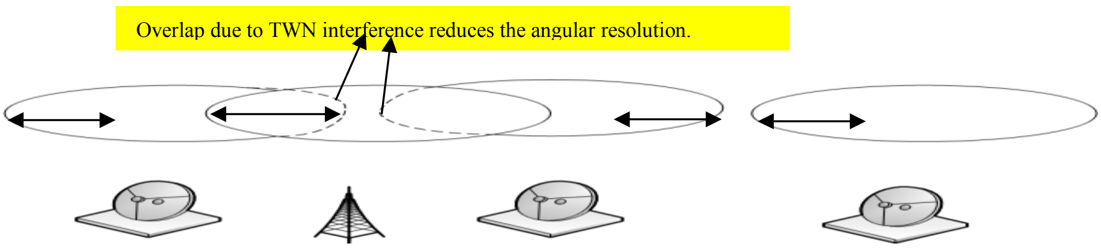

Figure 5-4: Converted ground based telescopes CEOxisting with terrestrial wireless network base stations.

The overlap decreases the radius of the GBTs virtual radio environment making a long baseline ineffective in enhancing the angular resolution. The CR can be used to address this drawback.

The virtual radio environment being considered in the proposed mechanism comprises MESs and converted GBTs. The proposed framework incorporating MESs is shown in Figure 5-5. The framework entities are the central computing entity (CCE) and the satellite astronomical interface (SAI). The satellite ground segment entities are: the visibility interface (VIF), the satellite visibility database (SVB) and the satellite-packet processor (SPP). The SVB holds information on MESs capabilities; and is aware of the visibility epochs and the duration of the LEO satellites. It communicates with the CCE via the VIF over the internet. The CCE is the computing infrastructure that identifies and selects the suitable MES.

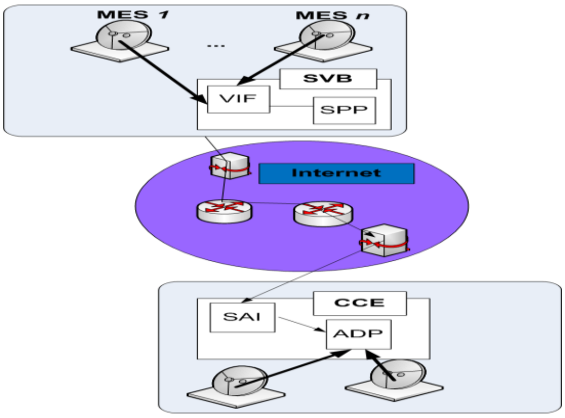

Figure 5-5: Interaction between entities.

5.3.3 Terrestrial Radio Astronomy Organisation – Improving HPC Utilisation

This chapter focuses on improving the terrestrial astronomy organisation's HPC utilisation. This objective is achieved by enhancing the power efficiency. The power efficiency is enhanced via interactions between the HPC and the cognitive TWNs.

An inference that can be drawn from [24, 90-91] is that increased access to information drives the design of intelligence algorithms that enhance the TWN subscribers QoS. The available information is used to design an intelligence mechanism that performs a network task. Asadi *et al.* [90-91] extend this view and propose a meta-cognitive model with multiple LAs requiring computational resources for training. In [90], the CR does not auto-generate new intelligent LAs. The CR's autonomy can be improved if LAs are auto-generated and trained without being restricted by the lack of available computational resources.

A TWN BS that incorporates generative artificial intelligence (GAI) [99] can auto-generate LAs, such as artificial neural-network multi-user detectors (ANN-MUDs). ANN-MUDs improve TWN throughput by enhancing the receiver SINR in MIMO-OFDM-SDMA systems [100]. They can handle different matrices, depending on the number of CR and TWN BS antennas.

The TWN base station decides on the ANN-MUDs's architectures used to obtain a low bit-error rate. ANN-MUDs are developed in the phases of data acquisition, training and output computation. The training phase is the most computationally intensive; and it determines the ANN weight that minimizes the output mean-square error. The ANN weight matrix is used for output computation; output computation requires less computational resources than in the training stage.

The TWN BS auto-generates new ANN MUD architectures to obtain a low bit-error rate for all sub-channels and MIMO-OFDM-SDMA states. However, the TWN BS's ability to train new ANN-MUDs is limited by the TWN BS's computational resources. Therefore, additional computational capacity is required when the auto-generated LAs cannot be trained by using TWN BS's current computational resources. The underutilised HPC can be used as a source of additional computational resources in this regard. HPC underutilisation occurs due to observation-limitation conditions [15, 101]. The ALMA HPC is reported in [15] to have a utilisation of 38%. In addition, according to the ALMA Cycle 3 report [101], the average estimated maximum fraction of observation time is 48.5%. Hence, the HPC is not processing GBT data for 51.5% of the HPC on- time. However, HPC sharing has not being considered for enhancing TWN cognitive capability.

The objective of enhancing HPC utilisation is realised by using a duty cycle as the controlling variable for HPC cognitive TWN interaction. The duty cycle is the controlling variable; because it addresses the underutilisation that might occur in a time slot. The HPC-cognitive TWN interactions is realised by the central computation module (CCM), the neural resource monitor (NRM) and the training resource-monitor (TRM). The CCM is located on the HPC; and it determines when the HPC is under-utilised. The TRM and NRM are internet-based entities. The NRM monitors the resource usage of ANNs on the TWN BS. It determines when the TWN BS requires access to additional computational resources.

The network scenario being considered is shown in Figure 5-7. In Figure 5-7, the BS belongs to the cognitive TWN. Figure 5-7 shows how a BS auto generates additional ANNs across epochs t_1, t_2 and t_3. The BS serves users U_1 , U_2 , U_3 and U_4 sharing one channel. The users share the channel to enhance spectrum utilisation. The subscribers have multiple antennas and use a varying number of antennas for data transmission. The TWN BS has a dynamic receiver matrix. The dynamic receiver matrix arises because of the changing number of subscriber antennas and the dynamic channel. The TWN BS has four intelligent learning algorithms at epoch t_1. At epoch t_2, the TWN BS has six LAs, having auto-generated an additional two LAs. The two auto-generated LAs are trained by the TWN BS using its computational resources. However, the TWN auto generates two additional LAs and transits from t_2 to t_3.

At epoch t_3, the BS does not have sufficient computational resources to train the two LAs that have been auto-generated. The TWN communicates this insufficiency of BS resources to the NRM on the internet. The NRM acquires information on the training demand and the details of the auto-generated LAs. During previous epochs, the NRM acquires information from the TRM, showing the status of HPC utilisation. The HPC utilisation status is used to verify whether the HPC is underutilised. In a case, where the HPC is underutilised, the NRM sends the TWN BS's training data and instructions to the HPC. The matrices of the developed LA are sent to the TWN BS.

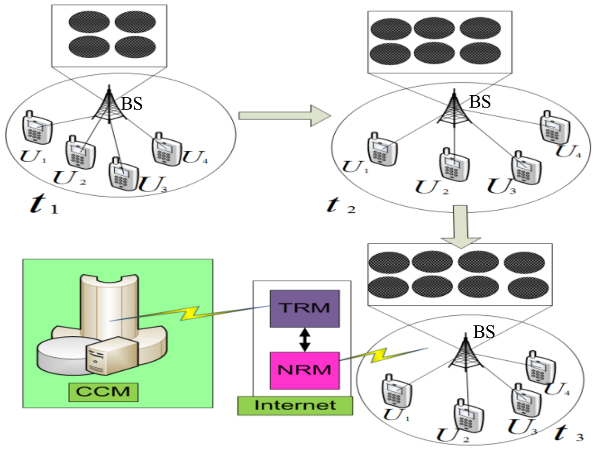

Figure 5-6: High performance computing infrastructure interactions with terrestrial wireless network incorporating generative artificial intelligence.

5.4 Performance Formulation

This section formulates the performance model for the mechanism proposed to optimise TRAOs for the terrestrial astronomy organisation. It is divided into three parts. The first part examines the TRAO daily spectrum utilisation and ISL daily transmit opportunities. The second discusses the improvement of angular resolution. The third focuses on the HPC utilisation performance model.

5.4.1 Terrestrial Radio Astronomy Organisation - Interference-Reduction

The discussion in this chapter investigates the TRAO spectrum utilisation and existing transmit opportunities. The TRAO daily spectrum utilisation over a 24 hour duration is:

$$Daily\ Spectrum\ Utilisation = \left(\frac{Daily\ Duration\ spent\ in\ TRAOs\ (hours)}{24}\right) \text{x } 100\% \tag{5.4}$$

The ISL daily transmit opportunities over a 24 hour duration is :

$$Daily\ Transmit\ Opportunities = \left(1 - \frac{Daily\ Duration\ spent\ in\ TRAO\ (hours)}{24}\right) \text{x } 100\% \tag{5.5}$$

5.4.2 Terrestrial Radio Astronomy Organisation – Enhancing Angular Resolution

The angular resolution is formulated for four scenarios i.e. scenarios 1, 2, 3 and 4. In scenario 1, TRAOs are conducted using GBTs realised from converted earth stations only. The angular resolution, $ð_1$ is:

$$ð_1 = \frac{\sum \lambda_{GBT}}{Baseline} \tag{5.6}$$

Where λ_{GBT} is the GBT wavelength.

In scenario 2, TRAOs are conducted using GBTs realised from converted earth stations and MESs. The use of MESs increases the baseline. MESs and converted GBTs can observe ASs at the same frequencies but at different locations. The angular resolution, $ð_2$ is:

$$ð_2 = \frac{\sum \lambda_{GBT} + \sum \lambda_{MES}}{Baseline \text{ x } (1 + BL_{inc})} \tag{5.7}$$

Where

λ_{MES} is the MES wavelength.

BL_{inc} is the percentage increase in baseline due to opportunistic use of MES for TRAOs ,respectively.

Scenario 3 considers a scenario in which TWNs are in the vicinity of MESs and the GBTs realised from converted earth stations. The TWN interference reduces the baseline , the angular resolution, $ð_3$ is:

$$ð_3 = \frac{\sum \lambda_{GBT} + \sum \lambda_{MES}}{Baseline \text{ x } (1 - BL_{dec})} \tag{5.8}$$

Where BL_{dec} is the percentage decrease in baseline due to spectral overlap of TWN.

In scenario 4, cyclostationary detectors are incorporated in the converted GBTs. Cyclostationary detectors reduce the effect of interfering TWNs in reducing the effectiveness of the baseline. They have been used in this case; because TWN signals are modulated and have well-known cyclostationary signatures detectable by CRs [20]. In this case, MESs aren't susceptible to TWN interference. The angular resolution $ð_4$, is:

$$ð_4 = \frac{\sum \lambda_{MES}}{Baseline \text{ x } (1 + BL_{inc})} + \frac{\sum \lambda_{GBT}}{Baseline \text{ x}(1 - BL_{dec}) \text{ x } (1 + BL_{cyc})} \tag{5.9}$$

Where BL_{cyc} is the percentage increase in baseline after cyclostationary module incorporation in the GBT.

5.4.3 Terrestrial Radio Astronomy Organisation – Improving HPC Utilisation

This chapter also formulates the probability of success when the HPC is used for executing the TWN training related computations. In this case, the under-utilised HPC is used to develop ANN-MUDs for the TWNs. Let Sa and Sc be the probability of having sufficient HPC resources and a functional CCM, respectively. The HPC– cognitive TWN relations aimed at training the TWN's ANN-MUDs, fails when:

1. The CCM fails, even though there are sufficient HPC resources. This happens with probability $Sc \text{ x } (1 - Sa)$ or
2. The CCM does not fail; but HPC resources are insufficient. This happens with probability $Sa \text{ x } (1 - Sc)$.

The probability of success of using the HPC to train the TWN's learning algorithms, Sp is:

$$Sp = 1 - (Sa \text{ x } (1 - Sc) + Sc \text{ x } (1 - Sa)) \tag{5.10}$$

Sc and Sa are modelled using the new modified Weibull distribution [102].

5.5 Performance Evaluation

This section presents numerical results to investigate how CRP incorporation optimises TRAOs. It is divided into three parts. The first part investigates the low interference ISL transmit epoch, duration and spectrum utilisation. The second discusses numerical results that show how CR incorporation in TRAOs enhances angular resolution and lowers TRAO costs. The third examines the improvement in HPC utilisation.

The improvement in HPC utilisation is investigated via three metrics. These are the HPC power efficiency (PE), success probability and how HPC–TWN relations enhance TWN throughput.

5.5.1 Interference Reduction - Analysis of Spectrum Usage and ISL Non-Interfering Transmission Epochs

This part discusses the performance of the interference-reduction framework and examines its feasibility. The performance metric is the latency of forwarding data through the network.

The low-interference transmission epochs and spectrum usage are examined by analysing data from the Karoo Array Telescope (KAT-7). The analysed data are those of observations conducted on 06/11/2012 (late afternoon), 07/11/2012 (early morning) and 16/02/2013 (morning and afternoon) referred to as periods 1, 2 and 3, respectively.

The observation duration (OD) of these epochs are 17:15:54.8 - 23:37:42.6, 16:13:50.4 - 20:17:30.6 and 08:42:05.3 - 16:40:55.7 for periods 1, 2 and 3, respectively. ISL de-activation on-board satellites is unnecessary for epochs outside the OD. The bands for the obtained data lie in 1.80-1.95 GHz. Therefore, the scheme is feasible for radio ISLs in the 1.80-1.95 GHz. Spectrum usage showing spectrum utilisation and the transmission opportunities are shown in Figure 5-7. The spectrum utilisation presented in Figure 5-7 describes the spectrum utilisation obtained for periods 1, 2 and 3.

It is also important to investigate the transmission opportunities that arise when GBTs switch between ASs. Hence, the back-to-back connection duration (D) seconds should be investigated. The back to back connection for periods 1, 2 and 3 are shown in Figure 5-8, 5-9 and 5-10, respectively. Satellites take advantage of opportunities presented in the back-to-back connection duration when they are aware of previously observed ASs.

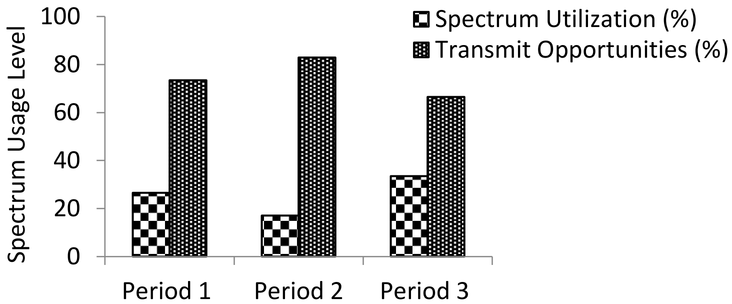

Figure 5-7: Periodic spectrum utilisation and transmission opportunities.

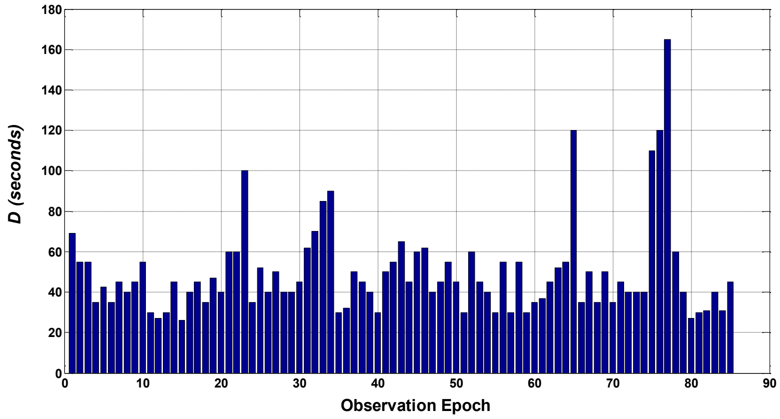

Figure 5-8: Back to back connection duration for period 1.

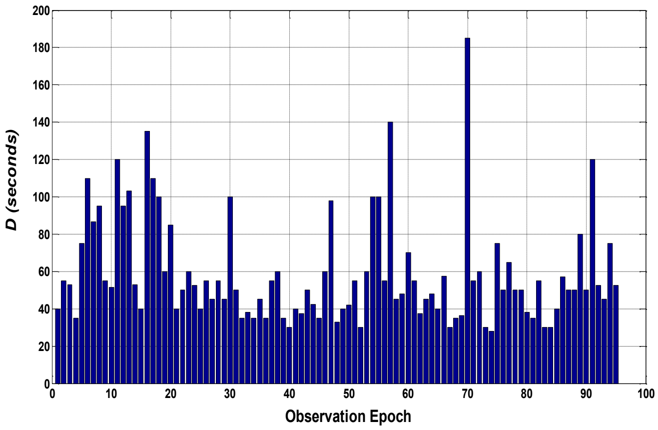

Figure 5-9: Back to back connection duration for period 2.

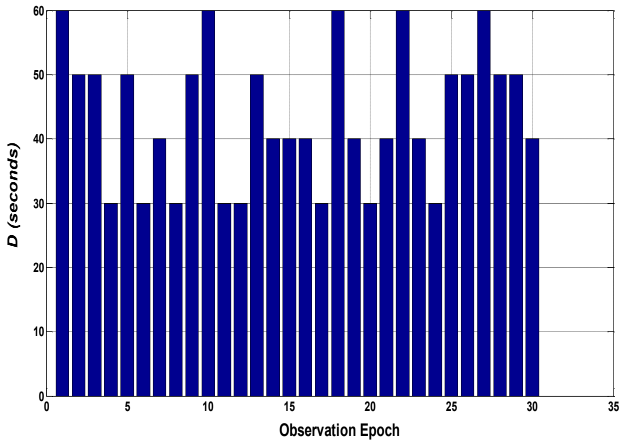

Figure 5-10: Back to back connection duration for period 3.

Therefore, the repetition of the procedures to further study selected ASs enhances satellite transmission opportunities, without interfering with TRAOs. Analysis shows that the average back to back connection duration obtained for periods 1, 2 and 3 are 49.5seconds 58.9 seconds and 43.7 seconds, respectively.

In addition, this chapter examines the existence of similarities in the order of observed ASs. The observed ASs are organised into strings and substrings. ASs strings and substrings are specified alongside observation dates. In composing the strings and substrings, ASs observed at other dates are compared with those observed on 16/02/2013. The strings, substrings and observation dates are:

1) Source String 1:{ $PKS\,1934-638$, $PKS\,J0010-4153$, $PKS\,J0022+0014$, $PKS\,J0024-4202$, $PKS\,J0042-4414$, $PKS\,J0059+0006$, $PKS\,J0044-3530$, $3C348$ }
2) Source String 2:{ $PKS\,J0240-2309$, $PKS\,J0252-7104$, $PKS\,J0303-6211$, $PKS\,J0309-6058$, $PKS\,J0318+1628$, $PKS\,J0323+0534$, $PKS\,J0351-2744$, $PKS\,J0405-1308$, $PKS\,J0409-1757$, $3C123$}
3) Source String 3:{$PKS\,J0408-6544$, $PKS\,J0420-6544$, $PKS\,J0440-4333$, $PKS\,J0442-0017$, $PKS\,J0444-2809$, $PKS\,J0453-2807$, $PKS\,J0519-4546$, $PKS\,J0534+1927$, $PKS\,J0635-7516$, $PKS\,J0744-0629$, $PKS\,J0831-1951$}
4) Source Strings 1, 2 and 3 are observed on {14/11/2012, 28/10/2012, 06/11/2012, 14/11/2012}, {06/11/2012, 14/11/2012} and {14/11/2012, 06/11/2012 (3 epochs)}, respectively.
5) The first seven elements of source string 1, first five elements of source string 1, the first nine elements of source string 2 and the first four elements of source string 2 repeatedly occur on {16/02/2012},

{05/02/2013}, {28/10/2012, 06/11/2012} and {06/11/2012, 05/02/2013}, respectively. The first eight elements of source string 3, the ninth to the twelfth element of source string 3 repeateadly occur on {28/10/2012 (2 epochs)}. The first eight elements of source string 3, , the ninth to the twelfth element of source string 3 and the , the ninth to the eleventh element of source string 3 repeatedly occur on {06/11/2012 (2 epochs).

These strings and substrings show that the observations of some ASs are repeated. Therefore, the proposed interference-reduction framework is feasible; and the LEO satellites can exploit these transmission opportunities when aware of previous ASDs.

5.5.2 Improving Angular Resolution- Performance Benefit and Cost Reduction Analysis

This section examines how the use of MESs can improve TRAO angular resolution. MESs are ground stations that can be used for TRAOs and satellite communications. In this thesis, the MES is furnished with a CR to enable transition between the two functionalities. The use of MESs is also expected to reduce the costs of conducting TRAOs. The cost is being considered from the perspective of infrastructure cost. This is because the terrestrial radio astronomy organisation does not need to engage in GBT construction. Hence, the improvement in angular resolution and cost reduction are investigated in the simulation.

The angular resolution is investigated for four cases. These are cases 1, 2, 3 and 4.

1) Case 1: The organisation has seven converted GBTs that observe in the IEEE UHF band, and are not susceptible to TWN interference. This case describes existing work [14] because it does not involve MESs. The baseline is 45 km.
2) Case 2: The organisation uses four converted GBTs and three MESs that can be observed in the IEEE UHF band. The addition of MESs increases the baseline to 90km. The converted GBTs are susceptible to TWN interference; and they incorporate an ideal cyclostationary detector. MESs are unaffected by TWN interference.
3) Case 3: The organisation uses three MESs and four converted GBTs that operate in the IEEE-C and IEEE-UHF bands, respectively. The converted GBTs are in the TWN vicinity and do not incorporate a cyclostationary detector. The MESs are not in the TWN vicinity. The baseline is 90 km.
4) Case 4: The organisation uses four converted GBTs and three MESs that operate in the IEEE UHF band. Both converted GBTs and MESs are in the vicinity of TWNs and incorporate an ideal cyclostationary detector. The baseline in this case is 90 km.
5) Case 5: The organisation uses four converted GBTs and three MESs operating in the IEEE UHF and IEEE C bands, respectively. The baseline is 90km. Both converted GBTs and MESs are in TWN vicinity; and they use ideal cyclostationary detectors.

The simulated results of the angular resolution are shown in Figure 5-11.

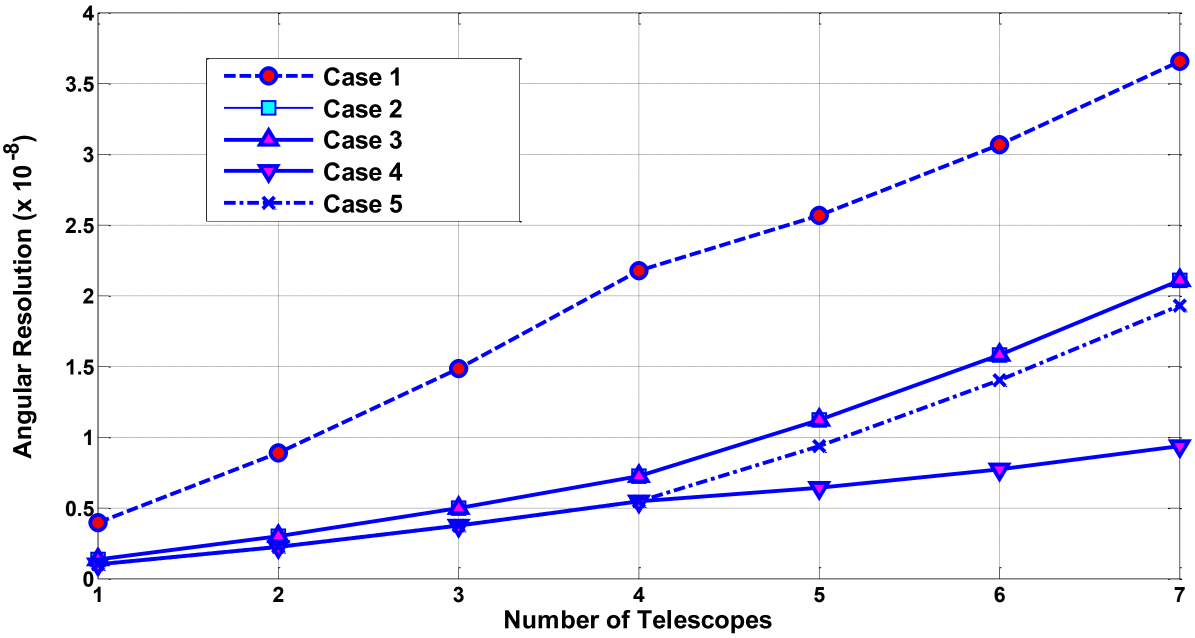

Figure 5-11 Angular resolution in different cases

A lower angular resolution is more beneficial for TRAOs. The angular resolution of cases 2 and 3 outperform that of case 1 by 67.5% and 59.2%, respectively. In addition, the angular resolution of cases 4 and 5 outperform that of case 1 by 75% and 66.7% on average, respectively. Hence, opportunistic access to MESs enhances angular resolution. An improved angular resolution is obtained when the MESs and converted GBTs use the IEEE UHF band, as may be seen in cases 2 and 4. This is because of the shorter UHF wavelength. Nevertheless, MES incorporation still enhances angular resolution. Therefore, the incorporation of MESs with cyclostationary detectors enhances the angular resolution. The results presented in Figure 5-15 show that the angular resolution can be enhanced by using MESs and CR cyclostationary detectors. Further analysis of the results presented in Figure 5-13 shows that the angular resolution in cases 2, 3, 4 and 5 outperform that of case 1 by 67.5%, 59.2%, 75% and 66.7% on average, respectively. It can be seen that the opportunistic use of MESs enhances the angular resolution. The incorporation of the cyclostationary module in cases 4 and 5 also enhances the angular resolution because of the interference reduction capability.

The terrestrial astronomy organisation's ownership costs is also simulated for five cases i.e. cases 1, 2, 3, 4 and 5 using the parameters in Table 5-2. The simulation results are presented in Figure 5-12.

Table 5-2: Cost Figures used to simulate ownership costs.

Component	Cost
Conversion of Unused Earth Station	100,000 - Hoare *et al.* [73]
Internet Link from CCE to SVB	1,000
Control Software Per GBT	20,000 (20% of Conversion Cost) - Kemball [103]
Cyclostationary Sensing Module	11,413 (assumed to be N9322C Agilent Spectrum Analyser)- LeMay [104]

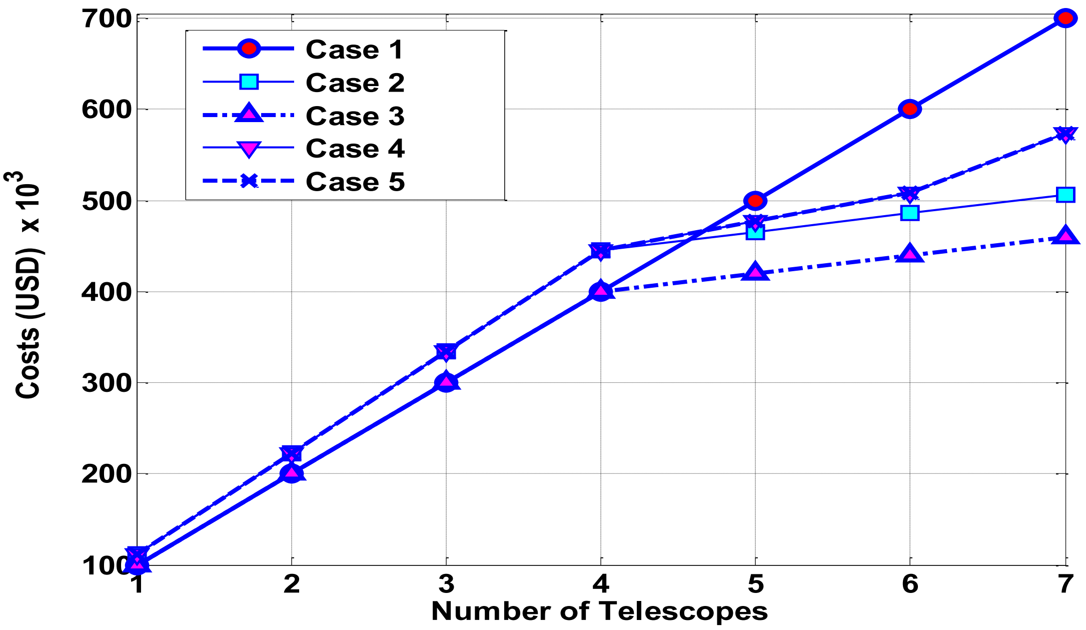

Figure 5-12: Terrestrial radio astronomy organisation ownership costs.

In Figure 5-12, it can also be seen that the cost in case 1 is lowest when there are up to four GBTs compared to cases 2, 3 , 4 and 5, respectively. This is because the GBTs in case 1 do not have any cyclo-stationary module, multi-mode software or internet link costs. The cyclo-stationary module increases the cost in cases 4 and 5. The inclusion of the control software and internet link increases the cost in cases 2, 3, 4 and 5. Therefore, the increased cost is due to the incorporation of the features proposed in this paper. The cost of adding the incorporated features increases the cost for the first four GBTs for cases 2, 4 and 5 compared to case 1. It does result in an increase for the cost comparison between case 1 and case 3. This is because in case 1 and 3, the first four GBTs are primary GBTs with similar functionalities. The average cost increase in cases 2, 4 and 5 compared to case 1 are the same and equals 11.4%. The cost increase is equal because only the cyclo-stationary module is added to the GBT in cases 2, 4 and 5.

The improvement in angular resolution is larger when GBTs and MESs use the IEEE UHF band as seen in cases 2 and 4 because of the shorter wavelength. Nevertheless, MES incorporation enhances angular resolution. Therefore, using an MES that incorporates the cyclo-stationary detector improves the angular resolution when its inclusion increases the baseline. Hence, terrestrial radio astronomy organisations should combine GBTs and MESs to reduce ownership costs and improve angular resolution.

5.5.3 Enhancing HPC Utilisation - Analysis of power efficiency and TWN Throughput.

This subsection examines how HPC sharing enhances power efficiency (PE). The PE is investigated for three scenarios. The first scenario, i.e. Scenario 1, is the PE of the time multiplex, as described in [15].

The second scenario, i.e. Scenario 2, describes the PE improvement when the HPC does not require any increase in power. The third scenario, i.e. Scenario 3, examines the PE improvement when the HPC power increases. The observation-limitation conditions affect an increasing number of GBTs. The simulation results obtained for the PE are shown in Figure 5-13.

In the simulation, it is assumed that each GBT present 450 samples from TRAOs. The TWN presents 20Kbits of data related to ANN training. The HPC consumes 200MW. The occurrence of observation limitation conditions reduces the number of observed samples by 30.1% on average.

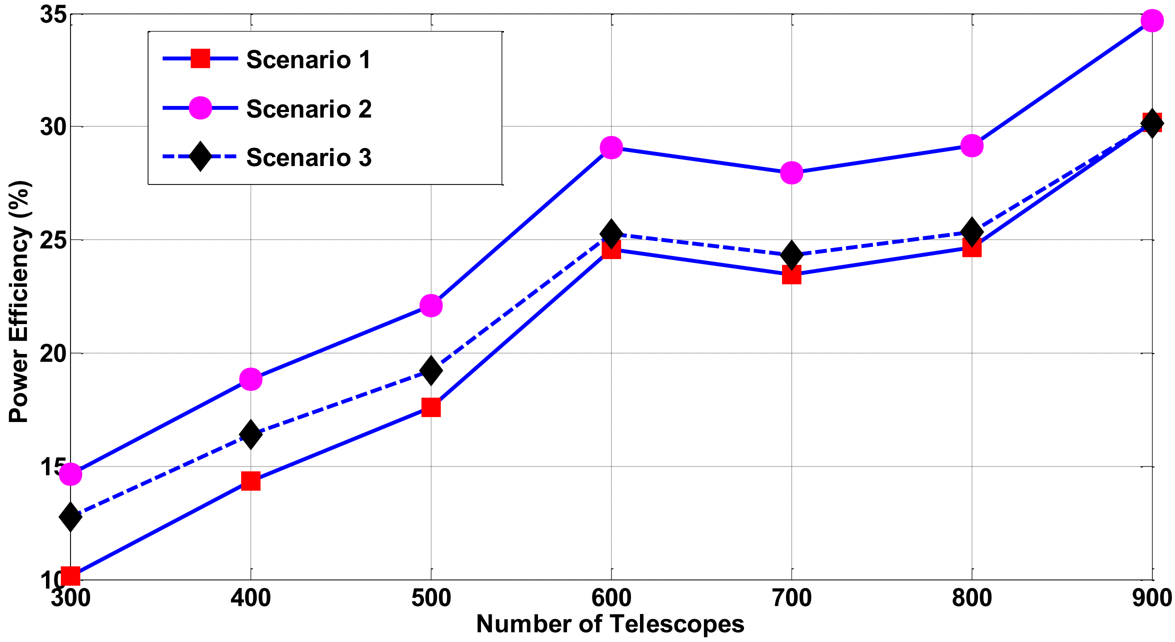

Figure 5-13: Power-efficiency performance.

Figure 5-13 shows that the PE increases with the number of GBTs; because more GBTs are affected by observation-limitation conditions. It is also observed that the HPC sharing improves the PE, when compared with the time multiplex. In addition, the HPC has the highest improvement in PE, when its use does not necessitate any increase in power. However, when the HPC requires an increase in power by up to 30%, the PE is reduced.

The PE exceeds that of the time multiplex by an average of 24.6%, 13.2% and 8.31%, when (1) there is no increase in HPC power, (2) HPC power is increased by 10%, and (3) HPC is power is increased by 15%, respectively. Therefore, an increase in the HPC power by 5% reduces the PE by 4.89 %.

It is also important to investigate the successful execution probability (SEP) due to HPC-cognitive TWN relations. The SEP depends on the available HPC resources and on the number of GBTs. Relations between the SEP and the number of GBTs for different HPC computational units are shown in Figure 5-14.

The SEP is also investigated. SEP is dependent on the number of GBTs and HPC computational units. The SEP is investigated for different number of GBTs and HPC computational units. An increase in the CU from 10 Kbits to 100 Kbits improves the SEP for the same number of GBTs. An increase in CUs from 10 Kbits to 100 Kbits improves the SEP from 0.0387 to 0.9087. The SEP also improves when the CU increases from 100 Kbits to 1000 Kbits. An increase in the CU from 100 Kbits to 1000 Kbits increases the SEP from 0.0726 to 0.9085. Hence, the availability of more HPC CUs improves the SEP.

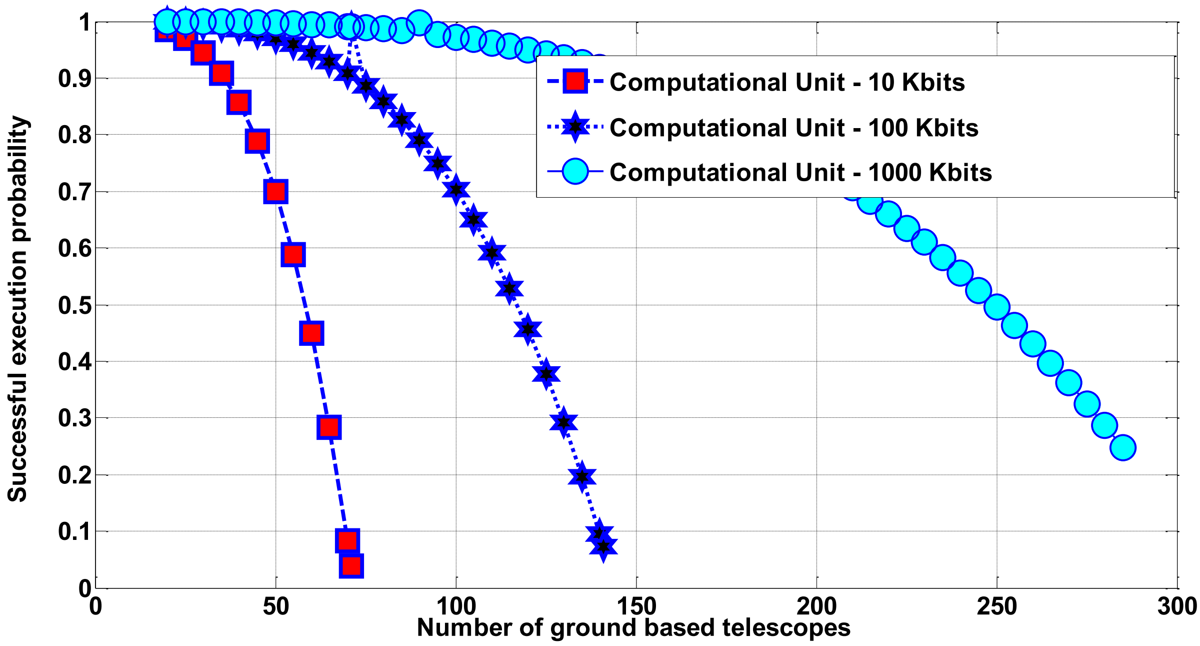

Figure 5-14: Success execution probability as a function of the number of ground based telescopes.

The influence of HPC–cognitive TWN relations on TWN throughput is also investigated. The TWN throughput is that obtained when the under-utilised HPC is used to develop ANN-MUDs. The simulation environment considers a scenario where three CRs share a 1 MHz channel to improve spectrum utilization. The simulated throughput is shown in Figure 5-15.

As seen in Figure 5-15, the throughput reduces with decreasing HPC computational units. The lowest throughput is obtained at epochs where available computational units cannot support the number of functional GBTs. The achievable throughput is minimum when the HPC has 10 Kbits and there are 71 GBTs and when the HPC has 100 Kbits and there are 141 GBTs.

From the results presented in Figures 5-14 and 5-15, it can be concluded that increasing the computational unit improves the SEP and the throughput. In addition, HPC-cognitive TWN relations enables the realisation of the goals of the unified architecture by enabling the TWN to make use of the underutilised HPC. This improves the HPC utilisation of the terrestrial astronomy radio organisation.

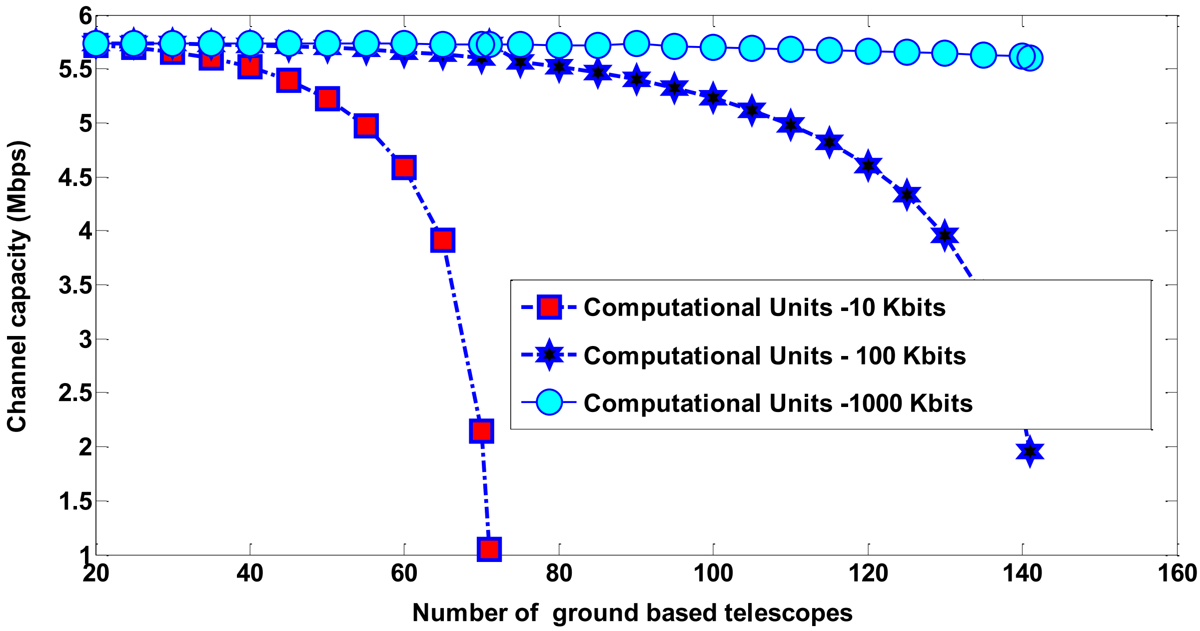

Figure 5-15: Throughput performance due to high performance computing infrastructure –cognitive terrestrial wireless network relations.

Furthermore, the thesis investigates the feasibility of HPC-cognitive TWN relations. HPC-cognitive TWN relations is feasible when there are non-operational GBTs. The use of MESs (with reconfigurable SDR) enables TRAOs to be conducted at different frequencies. The KAT-7 observation data are used for the feasibility analysis. The data on the observation day (OD) in mm/did/yy, observation duration (Dur) in seconds, number of inactive GBTs (NIT) out of the seven GBTs in KAT-7, the number of observed ASs (NSrcs) and observation frequency (OF) in MHz The obtained data are shown in Table 5-3.

Table 5-3: KAT-7 Observation data.

S/N	OD (mm/did/yy)	Dur	NIT	NSrcs	OF(MHz)
1	02/16/13	28740	0	31	1944.26562
2	11/06/12	22980	2	1	1920.24219
3	01/21/13	14700	0	1	1920.24219
4	10/14/12-10/15/12	31080	0	36	1920.24219
5	10/16/12	15180	0	12	1920.24219
6	10/28/12	36931	1	13	1827.078125
7	11/06/12-11/07/12	40800	2	66	1920.24219
8	11/14/12-11/15/12	36119	1	38	1920.24219
9	02/05/13	9846	1	11	1920.24219
10	02/11/13	18780	1	20	1920.24219
11	02/23/13	21730	0	23	1920.24219

Table 5-3 shows that KAT-7 GBTs are not operational for all ODs. The observations on 11/06/2012 were conducted at different times. It may be seen that sixty-six ASs are observed on two days spanning 11/06/12-11/07/12, and when using only five GBTs out of seven. Therefore, two GBTs are non-operational for 40800 seconds (11.33 hours). Further investigations show that the minimum non-GBT operational time is 2.73 hours for a single non-operational GBT on 02/05/2013. Analysis of the data for RAOs conducted on 11/02/2013 showed that the number of hours for which one GBT is non-operational amount to 5.22 hours.

Therefore, TWNs can access the HPC CUs for a minimum of 2.73 hours and a maximum of 11.33 hours. In addition, GBTs are capable of observing ASs at three OFs, i.e. 1944.26562 MHz, 1827.078125 MHz and 1920.24219 MHz MESs can also enable TRAOs at other frequencies because of SDRs' reconfigurability.

5.6 Conclusion

The discussion in this chapter has proposed CR-based mechanisms to enhance TRAOs. The considered terrestrial-radio astronomy organisation uses GBTs realised from converted earth stations. The organisation seeks to reduce GBTs - ISL interference, enhance angular resolution, and improve HPC utilisation. The reduction of TRAOs-ISL interference and the enhancement of angular resolution are joint objectives associated with optimising TRAOs. They are considered as strategies that optimise TRAOs; because they do not involve interactions with TWNs or CEOs.

The HPC sharing enables interactions between the HPC and the autonomous cognitive-TWN. The autonomous TWN can auto-generate ANN-MUDs. The occurrence of observation-limiting conditions enables the autonomous cognitive TWNs to use the under-utilised HPC. The under-utilised HPC is used to train the auto-generated ANN-MUDs. Relations between TRAOs and TWN improve HPC utilisation and TWN throughput. Hence, the mechanism proposed in this chapter meet the requirements of the unified architecture. The discussion in this thesis has also proposed mechanisms to enhance CR QoS in TWNs in Chapters 3 and 4. In the next chapter, the thesis presents mechanisms that enable CEOs to realise their spectrum-access objectives to enhance data transmission and to improve space-segment robustness. The chapter also examines relations between the CEO and TWN.

Chapter 6
Cognitive Earth-Observation Network Model (CEON)

This chapter presents a decentralised user interactive commercial earth observation network. The presented network model is called the cognitive earth observation network model (CEON). CEON aims to furnish users with ubiquitous real time access to desired earth climatic variables (ECVs). The contribution of this chapter is the use of the CR and intelligent mechanism to design the proposed CEON.

The discussion in this chapter presents mechanisms that enhance CEOs and are incorporated in CEON. CEOs requires spectrum access for ECV observation, ECV downlink and ECV uplink. ECVs could be either space ECVs or ground ECVs. Space ECVs are obtained by earth observation satellites while ground ECVs are obtained by ground stations. Examples of space ECVs are the surface wind vector and down welling solar irradiance [105]. Examples of ground ECVs are soil carbon and river discharge [105].

The space and ground ECV can be merged together to improve decision making in smart agriculture [79]. Fish *et al.* [79] recognise that future generation smart agriculture requires the merge of ECVs observed by satellite based and vehicle mounted sensors. The merging of space ECVs have been recognised to be valuable for improved environmental description [106]. In addition, technological advances have influenced ground station [107] and space segment design [108-109]. The evolution in the space segment has led to the use of small satellites such as CubeSats. CubeSats located in the lower earth orbit (LEO) can be used in the CEOspace segment. The ground segment of CEOnetworks hosts the earth station.

This section is divided into six parts. The first part discusses related work. The second describes the problem being addressed. The third presents the proposed mechanisms. The fourth formulates the performance model. The fifth discusses the simulation results. The sixth is the conclusion.

6.1 Related Work

The CEOspace and ground segment require different mechanisms to realise the goals of ECV data observations and access. The realisation of these goals require mechanisms that make CEOnetworks robust and enhance data transmission. Robust mechanisms are required to ensure that CubeSat modules can observe ECV data when demanded by the CEOuser. In addition, interference redcuction mechanisms are required to ensure high throughput ECV data transfer in the data uplink stage. The mechanism reduces interference between TWN and the ground station during ECV uplink. This section discusses literature on mechanisms proposed to enhance CubeSat functions suitable for CEOs.

This section discusses the algorithms proposed to enhance CubeSat operations. In [110], Wei *et al.* present a fractionated satellite (fracsat) that comprises a wirelessly linked processing and communication payloads. The processing payload is equivalent to the OCSS. It determines whether data should be forwarded to the ground station or to another satellite. In the event of a failure, the information on the failed module is removed from other modules. The removal of failed module information does not imply a restoration of the lost functionality, however. Additional mechanisms are required to restore the functionalities of the lost modules to the concerned fracsats. Such mechanisms should restore the functionality, prior to the launch of replacement modules.

Fracsat networks should be robust. The necessity of designing robust fracsats has led to the design of the F6MDA framework [111]. F6MDA executes resource management, fault management and multi-level security. It handles physical and software faults, in order to enhance system recovery and serve distributed applications. However, the F6MDA has challenges handling catastrophic subsystem failures that can occur in commercial earth observation systems. Furthermore, [111] presents a generic discussion of fracsats. An application of the F6MDA to different applications is required; because fracsats face different challenges for different applications.

Chu *et al.* [112] extend the discussion in [111] by considering the application of fracsats for earth observations. A multi-agent system fracsat, where each agent corresponds to a subsystem is presented in [112]. The multi-agent system model targets earth observations and it enhances system robustness. The fracsat comprises the mission-data processor, large volume data-storage component, data-relay component and high bandwidth-downlink component. The discussion in [112] determines the suitable fracsat architecture for earth observation platforms, using the analytical hierarchy process algorithm. The analysis shows that fracsats with wirelessly linked components have the best performance. The multi-agent system incorporates cognition to enhance cluster location management. This ensures that fracsats are quickly restored after executing a space-debris manoeuvre. However, additional work is required to achieve high uplink throughput for data communication in earth observations when using fracsats. Chu *et al.* [112] consider the need for a high bandwidth downlink and not high bandwidth uplink for a fracsat that interacts with a ground station.

Han *et al*. [113] describe a fracsat packet-communication system that incorporates an address-allocation system and an egress router. The router forwards the data between wirelessly linked fracsat subsystems. The packet communication's functionality handles inter-fracsat communications. The discussion here has focused on inter-fracsat communications, and not on the relations between fracsats and the ground segment.

The introduction of an address-allocation system into CubeSats raises further questions on the scalability of address systems when new modules are introduced into the system. This is important, in order to ensure that the module is integrated into the CubeSat, and that it communicates with them in the minimum time possible. This can be realised by ensuring that ground station to CubeSat uplink has a high throughput. An high throughput requires that ground stations should be able to access more bandwidth. However, the issue of bandwidth access requires further consideration.

The discussion above identifies that fracsats should be robust [110], and quickly recognise new modules [111]. The ground station should be able to transmit to fracsats at a high throughput. New mechanisms are needed to satisfy the spectrum-access objectives of CEOs that make use of CubeSats and ground stations.

Deployed earth-observation systems experience interference from TWNs [63-64]. The CR can be used to design algorithms that reduce interference between CEOs and TWNs. This has been considered for space applications [40,41]. Hence, the CR can meet CEO's objectives of low interference spectrum access and improving user performance. CR incorporation enables S-band meteorological radar to opportunistically access the idle LTE-A channels. The opportunistic access of idle LTE-A channels by the S-band meteorological radar enhances S-band utilisation.

Some systems have been envisaged for future earth observations. Examples of these are Pleiades [114], Sentinel [115], and the QB-50 nano-satellite constellation [116]. Pleiades comprises two small satellites that can transfer ECV data via the S or X-bands.

Sentinel satellites are to be launched incrementally by the European space agency. The European space agency envisages the launch of Sentinel 1, 2, 3, 4 and 5. Currently, there are four sentinel satellites, i.e. the Sentinel 1 and Sentinel 2, both comprising two satellites. Sentinel 1 and Sentinel 2 were launched in April 2014 and June 2015, respectively.

The QB-50 constellation aims to use 50 LEO nano-satellites. Although, QB-50 uses nano-satellites, it does not consider the goals of CEOs. The future intelligent earth observation system (FIEOS) which is suitable for CEOs, is presented in [80]. FIEOS aims to make ECV data access ubiquitous and responsive to user demands. It comprises end-user systems, LEO satellites and geostationary (GEO) mother satellites. FIEOS improves the spatial, temporal and spectral resolution of earth observations.

In FIEOS, GEO satellites receive data from LEO satellites; the received data are processed and sent to the end-users. FIEOS enables users to interactively demand and access ECV data in real time. Real-time ECV data can be accessed via low and high data rate channels from daughter and mother satellites, respectively.

The data from LEO satellite sensors is processed on GEO satellites. This reduces FIEOS's susceptibility to ground segment failure. However, relying on GEO satellites for data processing and high data rate increases the costs for low capital-space organisations with insufficient capital to launch GEO satellites.

The responsive and formal design process [43] overcomes the drawback of high space-segment costs. It is suitable for low capital-space organisations. The responsive and formal design proposes the use of LEO satellites. In [43], the mother and daughter satellites are located in LEO. Mother satellites process data received from daughter satellites. In [80], the mother satellite is the GEO satellite and the daughter satellite is the LEO satellite. The use of LEO pico- and nano-satellites reduces the costs for low capital-space organisations. However, new algorithms are required for scenarios comprising LEO mother and daughter satellites. In addition, robust algorithms are required to ensure continuity, when mother satellites in LEO become non-functional.

Furthermore, FIEOS constrains end-users to communicate with GEO mother satellites, when high data rates are desired. This increases data transfer latency because daughter satellites's data need to be transferred to mother satellites prior to downlink. In addition, uplink and downlink transmissions with daughter satellites should be done at high throughput. The X-band [44-45] and S-band [44] can be used for daughter-satellite downlink and uplink, respectively. However, S-band uplink from the ground station poses an interference risk to LTE-A, which also uses the S-band [68]. Hence, the co-existence of the CEOs and TWNs in the S-band spectrum requires interference-reduction mechanisms. In addition, the co-existence should also enhance spectrum utilisation.

Alternatively, CubeSats uplink and downlink communications can use the UHF band [108, 117]. However, the S-band is preferred, because of the increased uplink throughput. The use of the S-band is supported by the evolution of the modulation used in satellite communications. Satellite communication systems have evolved from using amplitude shift-keying modulation to quadrature modulation, with data rates of up to 3Mbps. New radios that use quadrature amplitude or phase-shift modulation are required for CubeSats. The use of the S-band for small satellite transmission has been recognised in [109]. Baceski *et al.* [109] recognise that the S-band transmission can enhance ground station to satellite uplink throughput. Therefore, CubeSats can realise high data-rate communications by sharing the S-band with TWNs, such as the LTE-A. This improves the S-band utilisation; and it allows the X-band to be used for new technologies, as the need arises.

CubeSats can be used in different space segment roles, as seen in the heterogeneous spacecraft network model [42]. Heterogeneous spacecraft network s can be classified as primary, secondary or hybrid. Primary heterogeneous spacecraft networks use CubeSats, as space segment components in earth-observation networks. Secondary heterogeneous spacecraft networks use CubeSats as multi-application space segment components. Hybrid heterogeneous spacecraft networks use CubeSats as space-relay nodes.

The classification shows that CubeSats can be used as dual role agents. CubeSats can be used as holistic agents (primary) or agents that enhance existing systems (secondary or hybrid). The discussion in [42] also examines the ISL communications requirements in small satellites. Technologies, such as IEEE 802.11, ZigBee and IEEE 802.15.4 are identified to be suitable. The IEEE 802.11 is considered suitable for ISLs, downlink and uplink communications in earth-observation networks. This is because of the high throughput of IEEE 802.11 compared to IEEE 802.15.4 and ZigBee. Although, the IEEE 802.11 spectrum is suitable because of its high throughput, it neglects enhancing the utilisation of licensed spectrum. A choice of sharing the licensed S-band between the TWN and CEOenhances S-band utilisation. It can be seen that the research has considered relations between space segment, ground segment and the TWNs from different perspectives. Some examined relations is presented in Table 6-1.

Table 6-1 : Small satellite mechanisms – applications and apectrum access.

	Components	**Mechanism & Application**	**Spectrum Access**
Boudjemaa [107]	Ground segment ; Stationary Ground station	Swarm intelligence for meteorological ground network planning.	Spectrum access objectives does not consider interaction with satellites and other ground stations.
Zafrara *et al.* [117]	Space segment of ALCUBESAT 1	Focus is on subsystem design and there is no focus on networking mechanisms.	Use of 433.92MHz for downlink only. No focus on uplink.
Baceski *et al.* [109]	Space segment ; Mobile space segment in LEO	Subsystem design and description, no focus on satellite networking mechanisms. Description of QB-50 subsystem.	Use of UHF and VHF for downlink and uplink, respectively. Advanced communication for S-Band. Incorporates SDR reconfiguration. Potentially suitable ISLs. Cognitive mechanisms not incorporated in SDR.

Faber *et al.* [42]	Mobile Space segment (LEO), Stationary ground segment.	Design of low cost multi-institutional network to increase user accessible ECV.	IEEE 802.11 spectrum is used for downlink and ISLs. Data transmissions in uplink is not considered.
Edmonson *et al.* [43]	Focus is on space segment. Small satellites in LEO are used as sensor networks.	Develops open systems interconnection framework for ISL communications. Formulation of the responsive and formal design process for small satellite systems, ISLs, distributed processing and reconfigurability are considered important features.	High bandwidth access requirement is recognised. Additional consideration is required for interference avoidance and user performance enhancement.
Palo [44]	Mobile space segment in LEO, stationary ground segment.	Design of X-band antenna for high data rate CubeSat downlink communications	X-band is used in the downlink for satellite – ground station communication.
Wei *et al.*[110]	Mobile LEO space segment and stationary ground segment.	Design of a data relay satellite system that comprises uplink, downlink and space routing mechanisms. Interaction with other satellites is also considered. Module failures is recognised to require adaptive mechanisms and requires further consideration.	Though additional features are recognised, the focus is on designing space routing mechanism.
Liolis *et al.* [65]	Space and ground segment ; non-geostationary (mobile) and geostationary (stationary). Stationary ground segment	Examining the suitability of CR for satellite communications not commercial earth observations. The authors present the CR satellite framework.	Suitable radio spectrum are the C, Ka and Ku bands. Identifying suitability of different cognitive radio spectrum sharing models for different scenarios in satellite networks.
Tercero *et al.* [66]	Mobile TWNs and Stationary ground meteorological radar.	Design of the dynamic frequency selection mechanism for interference reduction between IEEE 802.11 and radar in the 5.60-5.65 GHz spectrum	The focus is on the 5.60-5.65 GHz unlicensed band. Focus of spectrum access is on interference reductions and not enhancing ground station spectrum utilisation and throughput.
Deng *et al.* [67]	Stationary ground segment i.e. MIMO Radar and Mobile TWN users.	Space domain filter proposed for interference reduction between MIMO radar and TWNs.	Focus is on CEOxisting scenario. However, the space domain digital filter does not consider enhancing spectrum utilisation and throughput.

Small satellites have also been used to design CEOs networks. Examples of CEOnetworks are the Planet-Labs Flock constellation [39] and the Omni-Earth system [79]. According to Fish *et al.* [79], CEOs demand for ECV information should be incorporated in earth-observation system design. Fish *et al.* [79] discuss the business model and applications for future CEOs. However, unlike [39], the discussion in [79] does not examine the technological requirements for the delivery of commercial earth-observation services. CEOs networks are expected to transmit uplink data in the S-band [118]. The S-band is also required for LTE-A. CEO's networks transmitting in the S-band should not suffer any interference from, or pose interference to LTE-A.

The discussion in CEOs can be subdivided into three aspects. The first part describes the hardware component of earth observation systems [39]. The second focuses on the services rendered to users by CEO networks [79]. The third concerns spectrum allocation [118]. CEO networks should be robust, have a high throughput and low latency, to ensure that CEOdata are readily available. In addition, CEO network operators make more revenue when they sell more data. Therefore, CEOs networks require algorithms that enables them to provide users with more ECV from the space and ground segments.

The robustness of CEOs can be improved by using autonomous. Autonomous algorithms can enhance the robustness of CEOs that use LEO mother and daughter satellites. Robust algorithms have been proposed for improving space applications [119-122]. The autonomous nano-technology swarm framework (ANTS) [121] enhances space autonomy; and it is inspired by ant swarms. An ant swarm comprises a ruler, messengers, and workers; and it is capable of self-optimisation and self-protection capabilities. Swarms using ANTS can deal with faults by recognizing fault states, nominal health states and health-restoring actions.

However, ANTS is not designed for CEOs. The porting of ANTS to CEOs causes performance problems. For example, a delay occurs between fault occurrence and restoration to a healthy state. The delay increases the latency in CEOs networks, when data processing and demand occur simultaneously. Autonomous algorithms can enhance space CubeSat applications. These autonomous algorithms can be designed by using bio-inspired approaches. The use of bio-inspired algorithms is suitable for the CR, as seen in [25-30, 48-49]. The CR can be considered as the combination of SDR and bio-inspired algorithms.

Bio-inspired algorithms have been used to improve scheduling in earth-observation satellite applications [107, 123]. Mission planning for CubeSats that use SDRs should consider uplink and downlink. The uplink describes the ground station to fracsat transmission. The downlink describes the fracsat to ground station transmission. The fracsat-SDR downlink can be designed to transmit on the X-band [44]. The use of the X-band reduces interference between the CubeSat downlink and TWNs in the ground-station vicinity. S-band spectrum utilisation can be achieved by using the S-band for uplink transmission. This improves S-band spectrum utilisation and the ground station requires protection mechanisms to utilise licensed idle TWN S-band channels. A solution that enhances spectrum utilisation should enable the fracsat uplink to use the S-band and CEOxist with LTE-A.

A bio-inspired ant colony optimisation mechanism is described in [124]. Chen *et al.* [124] propose a decentralised ant-colony optimisation mechanism for ISL selection in LEO small satellite networks. The proposed mechanism enables link reconstruction and enhances network-resource utilisation. In [124], a small satellite selects the nearest small satellite that provides the highest ISL throughput when its ISL fail. The ISL selection advances [42]; because it reduces reliance on the control information uploaded from the ground stations. Satellites exchange information to identify the suitable neighbour satellite that meets communication requirements. However, the scheme considers non-fracsats. In fracsat networks, additional overhead arises because the transfer of control packets increases overhead. The algorithm in [124] selects only stable satellites; and satellites that do not meet this requirement are not selected. Therefore, satellites with resources, but without sophisticated station-keeping mechanisms to ensure orbital stability, are not selected.

Erlank *et al.* [85] discusses how bio-inspired mechanisms can be used to design robust small satellites, such as CubeSats. They recognise the similarities between satellites and biological organisms. Biological organisms are robust due to the mechanisms of genetic, information and functional redundancy. A robust small satellite architecture is presented in [85]. In the proposed architecture, a small satellite comprises field programmable gate arrays that are similar to the macromolecular machinery in cells. If a field programmable gate array fails, neighbouring field programmable gate arrays reprogram the failed field programmable gate array.

The discussion in [85] has focused on using bio-inspired mechanisms to design single low-cost reliable satellite units. Although, low-cost reliable satellites are desirable for CEOs, additional consideration is required to design robust mechanisms for networked low-cost reliable small satellites.

This thesis proposes an interactive CEOnetwork that fuses ground and satellite ECVs to meet future ECV demand. The CEOnetwork operator has access to multiple sensors on fracsats and ground stations. This thesis considers a scenario, where fused ground and space ECV data are transmitted to different locations through the space segment. The network scenario being considered in this thesis is that of a decentralised commercial earth observation network that uses an MGS in the ground segment.

The CEOspace segment should be robust to deal with catastrophic module failures, to ensure on-demand access to ECV data via the space segment. A bio-inspired mechanism that enhances the robustness of low-cost small satellites is presented in [85]. The discussion in [85] has not been considered in the context of networked fracsats in CEOs. In the event of catastrophic fracsat module failures, the space segment functionality is lost. A catastrophic failure is considered to occur when re-programmability is infeasible.

The lost functionality can be restored by launching replacement modules. However, the launch of replacement modules is at the expense of increased service downtime and launching costs. This thesis proposes a mechanism to ensure a functional commercial earth observation network – in the event of catastrophic module failures. The proposed mechanism ensures a functional space segment without immediate recourse to launching replacement modules.

Commercial earth observation networks require a high throughput for data transmission on the MGSs – fracsat uplink in the data uplink stage (DUS). This requires high bandwidth access to enhance DUS throughput. Commercial earth observation network operators have identified the S-band as being suitable to achieve a high uplink throughput [118]. The use of the S-band for the DUS enhances S-band spectrum utilisation. This is because the S-band is also being considered for LTE-A TWN. However, enhancing S-band utilisation increases the interference risk between TWNs and CEO. Hence, an interference-redcuction mechanism is required. This thesis proposes a mechanism that enables low interference access to the S-band by both TWNs and MGSs. Its ground segment hosts the MGS and the CEO existence mechanism.

Ants demonstrate the use of pheromones to determine the best paths for finding food sources. Pheromone motivated algorithms for small satellite applications can be found in [123, 125-126].

The following observations can be made on network architecture, data rate, and autonomy and spectrum allocation from the examined literature:

1) **Network Architecture:** LEO fracsats can be used in centralised or decentralised earth observation networks. Centralised earth observation networks are managed from a ground mission control centre. The mission centre passes control information to the space segment. In decentralized CEOnetworks, control information is exchanged via ISLs. Fracsats can also work with MGSs to enable ubiquitous ECV data access.
2) **Uplink Throughput:** It is important to increase MGS to fracsat throughput for faster data upload and reduced latency. A high uplink throughput can be obtained by using the S-band instead of the UHF-

band. The use of the S-band enhances throughput and spectrum utilisation. However, interference reduction algorithms should be designed to reduce interference between TWN and MGSs.

3) **Intelligent Mechanisms:** Bio-inspired mechanisms are suitable for enhancing space applications. Intelligent bio-inspired algorithms are required to design future robust CEOnetworks.
4) **Spectrum Allocation:** CubeSats transmitters are being designed to transmit in the S-band instead of the UHF. This transition is motivated by the desire to increase CubeSat data rates. Transition to higher bands also helps to design easily deployable ground stations [107]. Spectrum should also be allocated to CEOs in a manner that reduces interference with TWNs and enhances spectrum utilisation.

From the examined literature, it can be seen that issues such as the network architecture design, spectrum access and throughput enhancement has been widely considered for small satellite applications. These concerns are also important for commercial earth observations networks that use small satellites. Commercial earth observation networks should be robust and capable of high throughput ECV data transfer. Fish *et al.* [79] recognise that the delivery of commercial earth observation network services requires fusing ECV from multiple sensors. The mechanism in [85] enables the design of a robust architecture for an in-orbit satellite. In [85], the small satellite has a re-programming capability and can re-program its constituent field programmable gate arrays if they fail. This re-programming requires that another field programmable gate array possesses the transcript of the failed field programmable gate array. A catastrophic failure occurs when a field programmable gate array and the field programmable gate array holding its transcript fail at the same epoch. In such a case, the small satellite is not able to execute its function. This has not been considered in [85] but receives attention in this chapter.

6.2 Problem Description

This section is divided into two parts. The first and second parts describes the problem being examined for CEON's ground and space segment, respectively.

6.2.1 CEON-Ground Segment

The X-band spectrum is suitable for the uplink and downlink in CEOs. However, the use of the X-band does not enhance S-band spectrum utilisation. In addition, the choice of the X-band is based on the assumption that the S-band is fully utilised. This raises a notion of false spectral scarcity for the S-band spectrum. The X-band can be used for the downlink from the satellite to the ground station. The basis for this choice is the reduction of the overhead that arises when the S-band is used. The overhead could have arisen due to the satellite's need to access TWN spectrum usage data. It reduces the amount of ECV data that can be accessed in a visibility window. This thesis uses the S-band for the uplink. This choice improves S-band utilisation.

CEON's ground segment comprises the MGS that co-exists with the TWN. The MGS and TWN each have own S-band channels. The TWN comprises the TWN BS and TWN subscribers. In addition, the MGS has MIMO-OFDM capability.

Let c_g; $(c_g \epsilon C)$ be the MGS S-band primary channel. In addition, let $I^g \epsilon \{0,1\}$ and $I^{b'} \epsilon \{0,1\}$ be the state of c_g and $c_{b'}$, respectively. $I^g = 0$ and $I^g = 1$ signifies that c_g is idle and busy, ,respectively. $I^{b'} = 0$ and $I^{b'} = 1$ implies that $c_{b'}$ is idle and busy, respectively. The MGS reduces TWN interference from $c_{b'}$ channels when $I^g = 1, I^{b'} = 1$. MGS-TWN relations can also be described by $I^g = 1, I^{b'} = 0$. In this case, the MGS can bond c_g and $c_{b'}$ to enhance uplink throughput and spectrum utilisation. This chapter proposes a mechanism that predicts the idle state and duration of $c_{b'}$ channels.

6.2.2 CEON – Space Segment

The space segment comprises fracsats. Let α and $\hbar$ denote the set of fracsats and modules, respectively.

$$\alpha = \{\alpha_1, \dots, \alpha_y\} \tag{6.1}$$

$$\hbar = \{\hbar_1, \dots, \hbar_g\} \tag{6.2}$$

$$\alpha_r = \left\{S_{h_{\hbar_1}}^{\alpha_r,\theta_{\hbar_1}}, \dots, S_{h_{\hbar_s}}^{\alpha_r,\theta_{\hbar_s}}\right\}; \alpha_r \,\epsilon\, \alpha\, ; \hbar_s \,\epsilon\, \hbar \tag{6.3}$$

$\theta_{\hbar_1}$ and $h_{\hbar_1}$ are $\hbar_1$'s orbital inclination and altitude, respectively.

In addition, let $I\left(S_{h_{\hbar_m}}^{\alpha_r,\theta_{\hbar_m}}\right) \epsilon \{0,1\}$ denote $S_{h_{\hbar_m}}^{\alpha_r,\theta_{\hbar_m}}$; $\left(S_{h_{\hbar_m}}^{\alpha_r,\theta_{\hbar_m}} \,\epsilon\, \alpha_r\right)$'s functional status. $I\left(S_{h_{\hbar_m}}^{\alpha_r,\theta_{\hbar_m}}\right) = 0$ and $I\left(S_{h_{\hbar_m}}^{\alpha_r,\theta_{\hbar_m}}\right) = 1$ signify that $S_{h_{\hbar_m}}^{\alpha_r,\theta_{\hbar_m}}$ is functional and non-functional, respectively. The fracsat α_r cannot realise its goal when $I\left(S_{h_{\hbar}}^{\alpha_r,\theta_{\hbar}}\right) = 0$. The fracsat α_2's modules are functional when $I\left(S_{h_{\hbar}}^{\alpha_2,\theta_{\hbar}}\right) = 0$. The fracsat α_r can realise its goal if it can use α_2's functional modules. This chapter proposes a mechanism that realises this objective.

6.3 CEON Mechanisms

This section is divided into three parts; and it discusses the algorithms proposed for CEON. The first part presents the fracsat's components. The second part describes the mechanism proposed for CEON's ground segment. The third part presents the bio-inspired mechanism proposed for CEON's space segment.

6.3.1 Fractionated satellite components

The considered fracsat comprises three wirelessly linked modules with own power sources. These modules are the central computational module (CCM), weather-sensing module (WSM) and the wireless-communication module (WCM). The WSM comprises the sensors that observes the ECV data in the parameter observation stage. It sends WSM data to the CCM for processing.

The CCM carries out preliminary ECV data processing, executes the fracsat's algorithms and determines the WCM transmission parameters. It processes and forwards the ECV data; and it determines the WCM's transmission parameters.

The WCM is an SDR that comprises ISL, downlink and uplink sub-modules. The ISL sub-module enables communications between the WCMs of fracsats. Downlink and uplink sub-modules enable transmission to and reception from the MGS, respectively. The WCM receives information on the parameters of other fracsats, and sends them to the CCM. The CCM uses the parameters of other fracsats to determine suitable replacement modules in other fracsats. It also computes the WCM's downlink and uplink parameters.

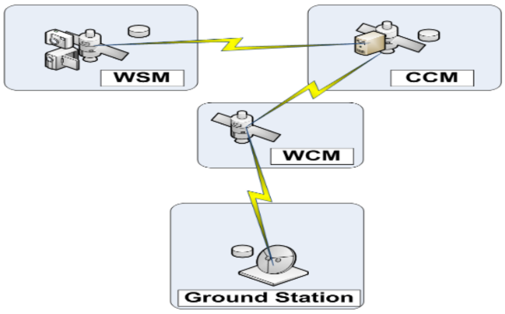

Figure 6-1a: Module composition of a fracsat unit

In the discussion that follows, for α_r the first module i.e. $\left(S_{h_{k_1}}^{\alpha_r,\theta_{k_1}}\right)$ is the WSM. The WCM transmits only processed ECV data and there is no link between a fracsat's WCM and WSM.

Relations between CEON's fracsats units are shown in Figure 6-1b. The fracsats 1 and 2 in Figure 6-1b can communicate with MGS 1 and MGS 2. The MGSs can transmit ECV via bonded MGS and TWN channels. In Figure 6-1b, the MGSs are in different locations and exchange ECV via the space segment. The transmission of ECV through the space segment reduces the load on the internet.

In Figure 6-1b, the end user at MGS 1 requires ECV data. The required ECV data necessitates ECV observation at MGS and α_2. The observation instructions are sent by MGS 1 to α_1. The fracsat α_2 receives the observation instructions from α_1 via the ISL. In addition, the fracsat α_2 sends observation instructions for ground ECV observation to MGS 2. MGS 2's ECV are sent to α_2 on the uplink at high throughput and merged with the ECV observed by α_2.The merged ECV is sent to the user at MGS 1 on the downlink via the X-band.

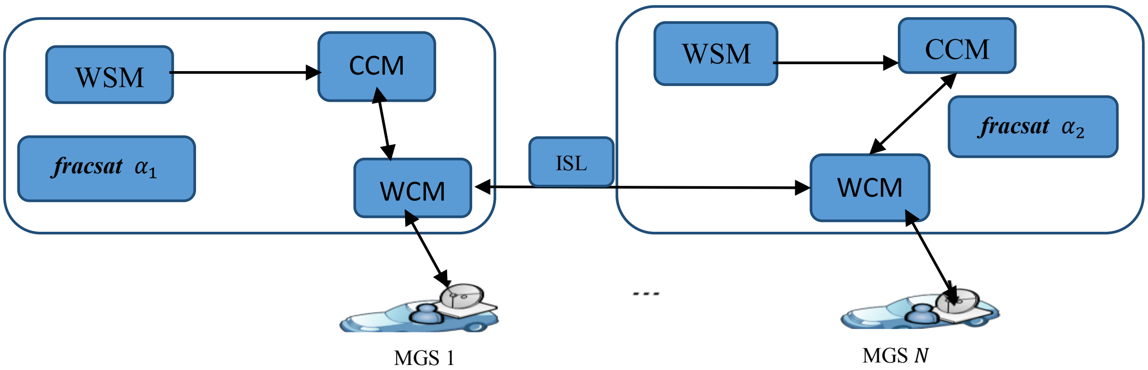

Figure 6-1b: Interaction between the space and ground segment entities in proposed network model.

6.3.2 Ground Segment – Proposed Mechanism

This thesis proposes the incorporation of a spectrum-prediction mechanism in the MGS. The MGS uplink to the WCM can occur in two modes i.e. the primary and the hybrid modes. In the primary mode, the MGS transmits to the WCM using only its own allocated S-band channels. The MGS bonds own allocated S-band channels and idle TWN channels in the hybrid mode. The MGS predicts the idleness of TWN channels using an ML-FNN.

6.3.3 Space Segment – Motivation for Bio-Inspired Mechanisms

The robustness of ants is enhanced by multiple-nest relations in polydomy [127-129]. Polydomy enables ant colonies to survive environmental pressures and changes that threaten their existence by increasing nest diversity. Straub *et al.* [130] identify that pesticide and environmental pressure threaten ant survival. Shea-Weller *et al.* [131] recognise that collective behaviour enables ant communities to develop spatially-specific advantages. The collective behaviour of ants enables ant colonies to respond to different environmental threats. The discussion in [131] identifies some mechanisms in ant colonies that suggest that polydomy is cognitive. The identified mechanisms are environmental probing, emigration and flexible-task allocation. Shik *et al.* [132] present a suitable mathematical model of ant polydomy.

Environmental probing is the examination of the external environment of an ant colony. It aims to determine the risk of mortality and is carried out by scouting ants. Scouting ants are workers that explore the external environment, to pro-actively identify a suitable replacement nest for emigration purposes.

Emigration enables an ant community to move and change its location in response to increased predation threats. There are two types of emigration: i.e. emergency emigration and forced emigration. The execution of emigration solves the nest-selection problem for ant colonies. Emigration can also be triggered by workers or the loss of a queen. An ant colony can select suitable neighbouring sites, when there is worker loss in emergency emigration. Queen loss threatens continued colony existence. It can arise due to death or disease and results in forced emigration.

Flexible-task allocation is important for the selection of new scouting workers by ant nests. Scout workers become lost when they visit high-mortality rate locations. The loss of scout workers enables workers in the sending nest to adjudge that a location is unsuitable for future emigration. However, the nest requires additional scout workers to determine the mortality risk of alternative locations. The ant nest uses task-allocation mechanisms to select new scout workers that can explore other locations. Scouting in ant colonies presents a form of learning mechanism in ant colonies. The association of emigration choices, scout ant election with nest selection describes a form of learning mechanism.

6.3.4 Space Segment – Proposed Mechanism

The space segment of the fracsat network being considered is shown in Figure 6-2. Figure 6-2 presents a fracsat network in LEO. The module of each fracsat in Figure 6-2 is self-aware and incorporates the architecture proposed in [85]. The fracsat modules are wirelessly interconnected. Inter-WCM communication is realised via ISLs. In Figure 6-2, the WSM and CCM can be either damaged (D) or severely damaged (SD).

The WCM is assumed fully functional. A damaged or severely damaged WCM implies that the fracsat is lost and is unreachable. This is because only the WCM is equipped with antennas suitable for uplink and downlink.

In the discussion, the queen is the CCM; while the WCM and WSM are the workers. A super-colony is a network of fracsats under the control of an high-capacity CCM, i.e. the master module (MM). The CCM determines the WCM's configuration parameters. The WSM and the CCM are jointly regarded as a CR.

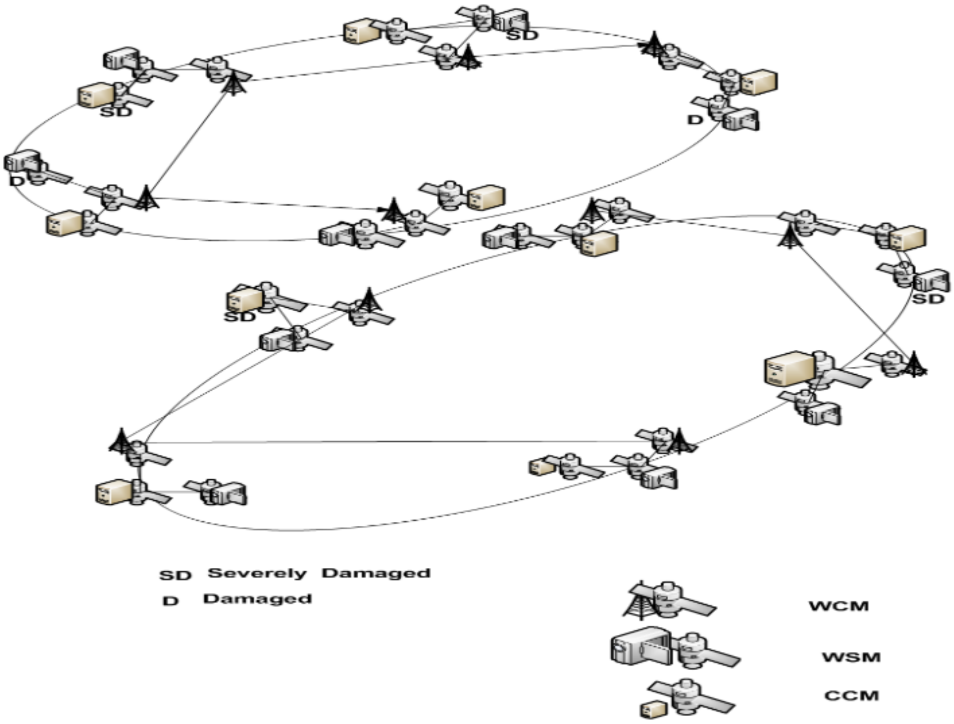

Figure 6-2: Constellations of fracsats where each fracsat uses the existing transcription based mechanism.

An earth-observation network with a host segment incorporating the proposed polydomy bio-inspired mechanism, is shown in Figure 6-3. The network shown in Figure 6-3 has three super-colonies, i.e. super-colony 1, super-colony 2 and super-colony 3. Each super-colony in Figure 6-3 has WSM, WCM and CCM. There are two types of computational modules in the presented space segment. These are the CCM and the master module (MM). The MM is a type of CCM, but with a higher capacity. Each super-colony has two CCMs and one MM. Each CCM executes the cognitive switching functionality and exchange information to determine the CCM to MM transformation. The polydomy bio-inspired algorithm executes cognitive switching and environmental probing in the identification and selection of replacement-functional modules.

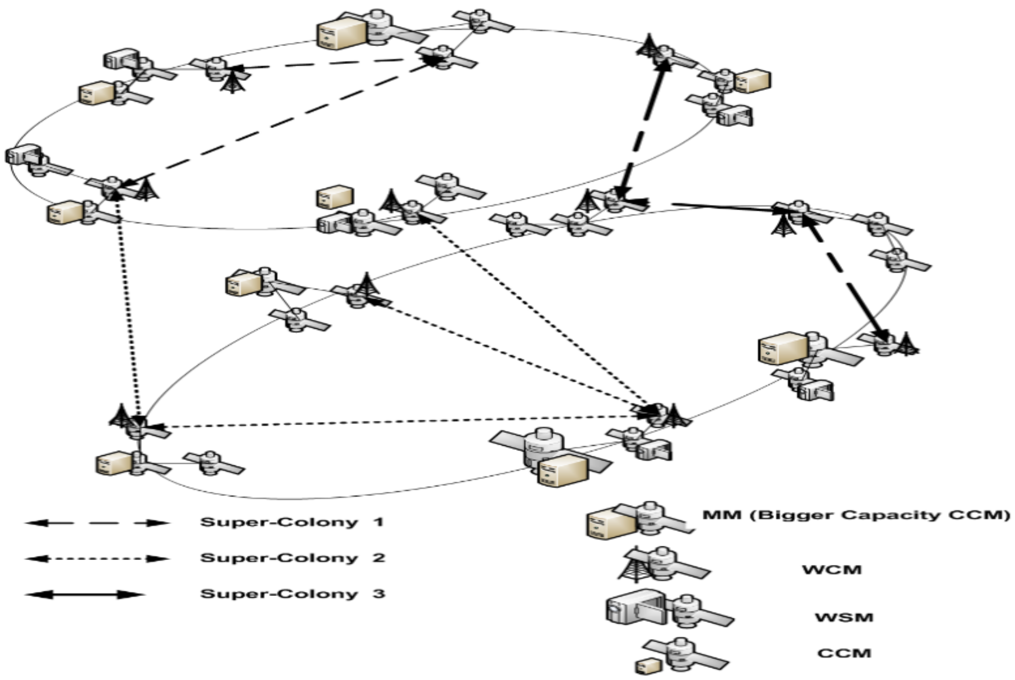

Figure 6-3: Space segment of proposed network model.

Cognitive switching enables the fracsat to make a decision as regards joining an existing super-colony or to form a new super-colony. Being self-aware, the fracsat can determine whether it has a sufficient capability, to develop suitable responses to environmental threats. The cognitive switching functionality is inspired by discussion in Straub *et al.* [129]. Straub *et al.* [129] point out that the reduction of immune repertoire precedes ant super-colony formation. The architecture in [85] can be used to develop a fracsat that is immune to catastrophic module failures. However, the architecture in [85] does not consider a scenario when multiple micro-controllers become damaged simultaneously. This thesis considers a scenario, where multiple micro-controllers become damaged simultaneously – resulting in a scenario where micro-controller re-programming becomes challenging. Cognitive switching enables a fracsat to determine if it can re-program failed components in other modules of the fracsats.

In forming a super-colony, the CCMs receive information from other fracsats. The received information is used to determine potential fracsats with which they can form super-colonies. The CCM also uses the received information to decide on a CCM that can be used as an MM. The identification of suitable super-colony relationships is executed by the environmental-probing functionality. In the environmental probing stage, the fracsat evaluates the metabolic rate. The consideration of the metabolic rate is motivated by the work of Shik *et al.* [132]

The metabolic rate is the ratio of the CCM's actual number of computations to its pre-determined maximum number of potential computations. It is computed for a given time window. A CCM with an high metabolic rate has low residual capacity and is unsuitable as an MM in its super-colony. A CCM with a low metabolic rate has high residual capacity and is suitable as an MM in its super-colony.

6.4 Performance Formulation

The section formulates CEON's performance model. It investigates how spectrum prediction and the polydomy-inspired algorithm can enhance the ground and space segment, respectively. The performance metrics for CEON are the, MGS uplink throughput, uplink latency and amount of accessed ECV data. It is divided into two parts. The first and second parts formulate the performance model for the ground and space segments, respectively.

6.4.1 Ground Segment – Uplink throughput and Latency

The incorporation of spectrum prediction enables the MGS to bond c_g; $(c_g \epsilon\ C)$ and idle $c_{b'}$ channels for the uplink in the hybrid mode. The MGS uplink occurs over c_g with transmit gain, (h_g^t) ,transmit power, (p_g^t), interference gain (h_g^{in}), and interference power,(p_g^{in}). The MGS primary mode uplink throughput Th_{nb} is:

$$Th_{nb} = B_g \log_2 \left(1 + \frac{|h_g^t|^2 p_g^t}{|h_g^{in}|^2 p_g^{in} + \sigma^2}\right) \tag{6.4}$$

Where B_g is the bandwidth of c_g in Hz.

With channel bonding,the MGS accesses idle b'channels and its hybrid mode uplink throughput, Th_b is:

$$Th_b = B_g \log_2 \left(1 + \frac{|h_g^t|^2 p_g^t}{|h_g^{in}|^2 p_g^{in} + \sigma^2}\right) + \sum_{b'=1}^{b-1} B_{b'} \log_2 \left(1 + \frac{|h_{b'}^t|^2 p_{b'}^t}{|h_{b'}^{in}|^2 P_{b'}^{in} + \sigma^2}\right) \tag{6.5}$$

The MGS uplink latency is:

$$Uplink\ Latency = \begin{cases} \frac{Size\ of\ ECV\ on\ uplink}{Th_{nb}}\ ; & No\ channel\ bonding \\ \frac{Size\ of\ ECV\ on\ Uplink}{Th_b}\ ; & channel\ bonding \end{cases} \tag{6.6}$$

6.4.2. Space Segment - Amount of Accessible Data

CEOnetwork operators aim to generate revenue by selling more ECV data to subscribers. The robust space segment should enable CEON to supply more ECV data to subscribers on demand. The thesis investigates how the incorporation of the robust polydomy-inspired algorithm enhances accessible ECV data compared to FIEOS [80]. A space segment comprising fracsats whose modules use [85] and the proposed mechanism are considered. In formulating the accessible ECV data, it is assumed that the WSM captures data using multiple sub-components. In addition, let D_{α_r} be the amount of ECV generated by α_r's WSM. The ECV data accessed from WSMs in the space segment, L is:

$$L = \sum_{r=1}^{y} I_{\alpha_r} D_{\alpha_r} \tag{6.7}$$

Where $I_{\alpha_r} \epsilon \{0,1\}$ is the WSM indicator. $I_{\alpha_r} = 0$ and $I_{\alpha_r} = 1$ signify that α_r has a non-functional and functional WSM, respectively.

6.5 Performance Evaluation

This part discusses simulation results and is divided into two parts. The first and second part discuss simulation result for the ground and space segment, respectively. The space segment is assumed to have fracsats (with three modules) located in altitudes lying in the range 500km-700km. The fracsats's WCMs use frequencies in the range (8-12) GHz for downlink. Hence, the space segment can support up to 10 fracsats. The WCM-MGS downlink has a link margin of 7.11dB. This link margin is obtained given an WCM altitude (500km), WCM parabolic antenna diameter (2cm), aperture efficiency (65%) ; MGS antenna diameter (9m), WCM transmit power (2W) at 8GHz. The expected received signal level is -72.89dB and the expected MGS sensitivity is -80dB.

The WCM-MGS downlink has a link margin of 4.8dB given WCM altitude (700km), WCM parabolic antenna diameter (2cm), aperture efficiency (65%) ; MGS antenna diameter (11m) at 12GHz. The expected received signal level is -75.2dB and the MGS sensitivity is -80dB.

6.5.1 Ground Segment

This part examines the MGS prediction accuracy, throughput, latency and the data availability. The MGS uses a well-trained ML-FNN for performing the spectrum prediction. Channels predicted to be idle by the ML-FNN are bonded with primary MGS channels. The channel bonding enables MGS primary to hybrid mode transition. The ML-FNN is developed and trained by using the MATLAB neural network object-oriented framework. The ML-FNN parameters are shown in Table 6-1. The ML-FNN performance is examined by comparing the predicted and the expected output values. The predicted output is the connection duration of channels to be bonded with primary channels by the MGS. A comparison of the predicted and expected values is presented in Figure 6-4. In Figure 6-4, the connection duration has been normalised. The maximum connection duration is 18.4ms. The result shows that the MGS reduces interference caused to the TWN. This is because the predicted output is less than the expected output.

Table 6-1: ML-FNN design parameters.

ML-FNN Layer	**Number of Neurons**	**Transfer Function**
Input Layer	10	*tansig*
First Hidden Layer	40	*tansig*
Second Hidden Layer	30	*tansig*
Output Layer	1	*purelin*
Additional ML-FNN Training Parameters		
Training Algorithm		Levenberg-Marquadt
Percentage of training samples		60%
Percentage of validation samples		20%
Percentage of testing samples		20%

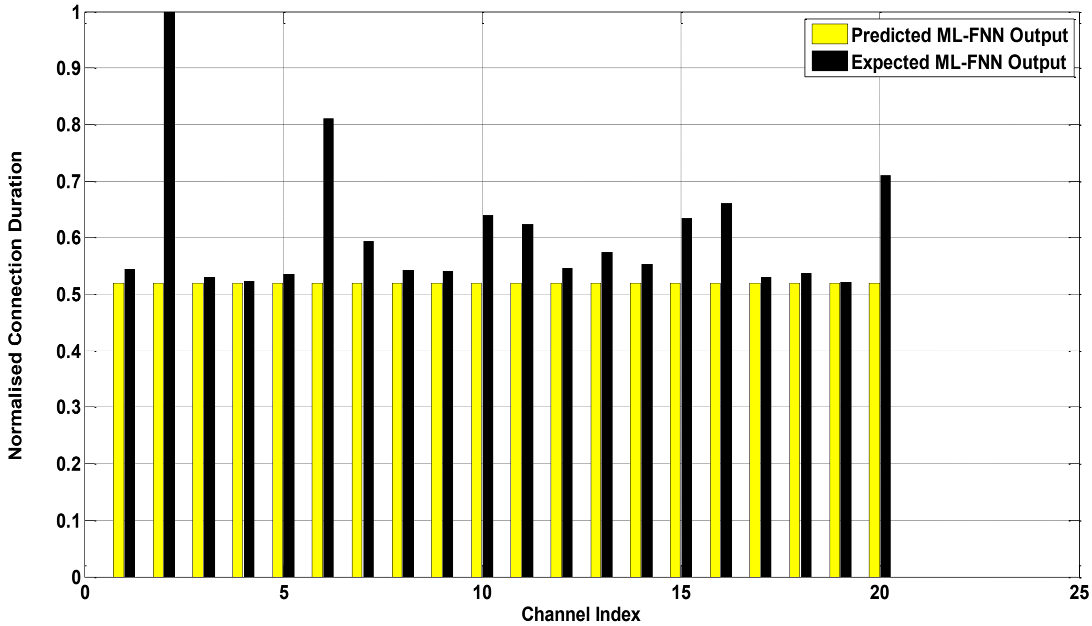

Figure 6-4: MGS ML-FNN prediction performance.

The MGS throughput of interest is the uplink throughput. MGSs in CEON can operate in primary or hybrid modes. The throughput performance of the MGS is shown in Figure 6-5. In the simulation, the MGS is assumed to have channel bonding capacity in primary and hybrid modes. Hence, the MGS can transmit over multiple channels in the primary modes.

Figure 6-5 shows that the MGS uplink throughput increases with the number of MGS channels. An increasing number of channels implies that MGSs use more primary channels. In the hybrid mode, the increasing number of primary channels are bonded with the idle TWN channels. Hence, an increased uplink throughput is observed with the number of increasing channels, when the MGS is in hybrid mode. The MGS in hybrid mode has a higher throughput, due to the increased accessible bandwidth. The prediction of more idle channels implies low spectrum usage by LTE-A subscribers. This enables the MGS to also use an increased transmit power, while upholding the CPP.

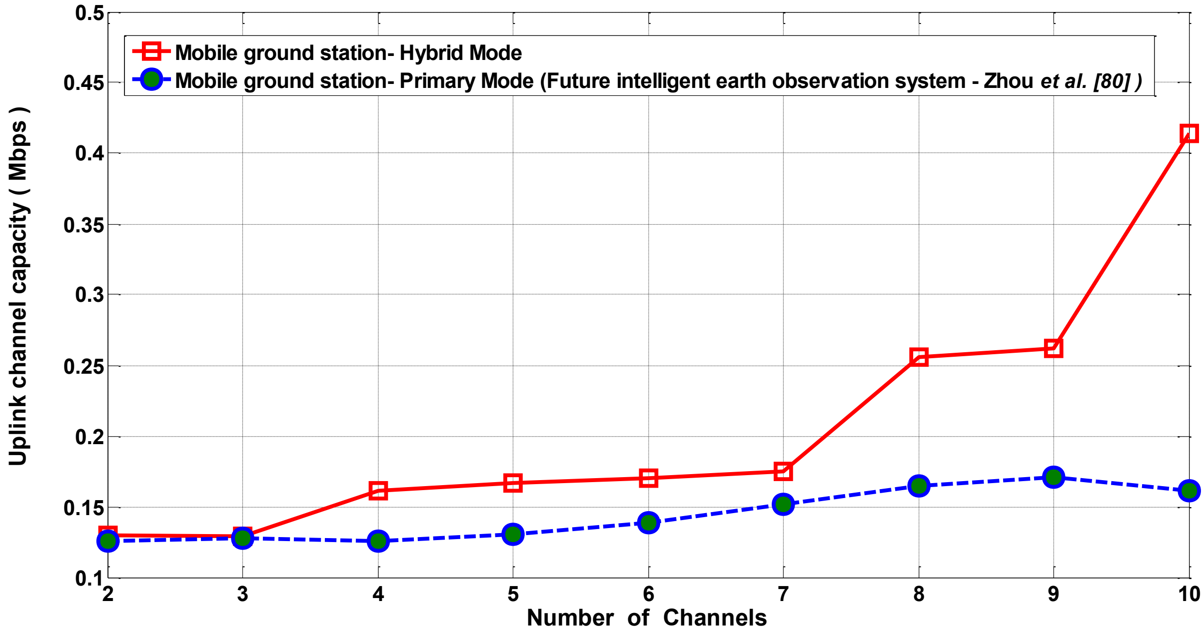

Figure 6-5: MGS uplink channel capacity.

This simultaneous increase in bandwidth and power due to low PU spectrum usage by MGS enhances the throughput. Further investigations show that the average throughput is enhanced by 60% when the number of channels accessed by the MGS ranges between 5 to 9 channels. In addition, spectrum-prediction techniques improves the MGS overall uplink throughput (for all channels) by 40.6% on average.

The increased uplink throughput reduces ECV forwarding latency in CEON. In examining the latency, the scenario considered is one in which the user requests ECV that necessitates joint observation. The joint observation is executed by sensors aboard the WSM and the MGS. The requesting MGS receives ECV data from the WCM. The requested ECVs traverses fracsats 1, 2 and 3 and is merged at fracsat 4. The merged ECV is sent through fracsats 6, 7, and 8. Fracsat 8 sends the merged ECV data to the user at the requesting MGS. The MGS and WSM capture 68 Kbits and 90 Kbits of ECVs, respectively. The mean ISL throughput between satellites in the simulation is of used in the simulation is 7.41Gbps.

This chapter also investigates how CR incorporation reduces uplink latency. Figure 6-6 shows that the uplink latency reduces when the MGS is in hybrid mode, due to the increased throughput.

The uplink latency is reduced when the MGS is in hybrid mode because of the increased uplink throughput. The use of channel bonding reduces uplink latency by up to 696.6ms. The reduction in latency, when the MGS accesses more channels in primary mode, without prediction is observed to be 199.9 ms.

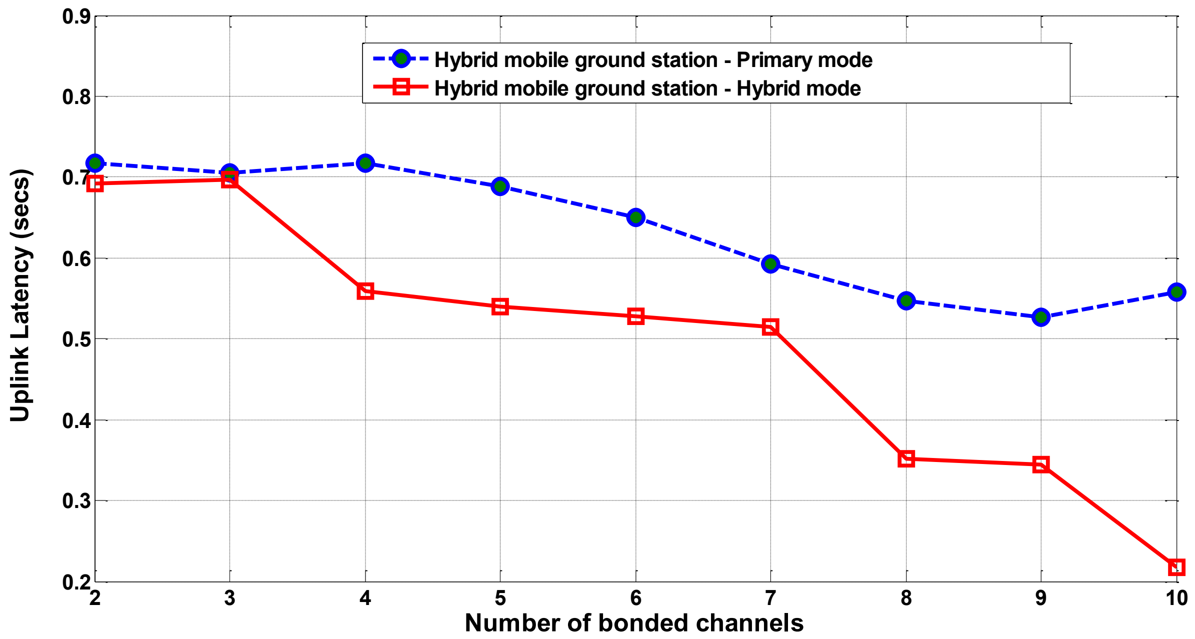

Figure 6-6: Uplink latency in proposed commercial earth observation network model.

Further investigations show that the uplink delay is decreased by 18.6% on average, when the MGS is in hybrid mode. Primary mode MGSs are used in the FIEOS, where the ground station does not incorporate CR spectrum prediction. Therefore, incorporating spectrum prediction in MGSs, results in an enhanced QoS. This is because the uplink throughput is enhanced by 60%. In addition, the uplink latency is reduced by 18.6%.

6.5.2 Space Segment

The incorporation of the proposed bio-inspired algorithm is expected to enhance the amount of data accessed from the space segment. In investigating the accessed ECV data, four scenarios are considered, these are:

1) Scenario 1: This case considers an WSM that uses the algorithm in [85]. The occurrence of catastrophic failures reduces WSM's ability to capture requested ECV by 11% on average.
2) Scenario 2: In this case, the loss of WSM re-programmability reduces the ability to capture the requested ECVby 6% on average.
3) Scenario 3: The space segment incorporates the proposed polydomy-inspired mechanism. The WSM experiencing catastrophic failures can access sub-components of other WSMs via the MMs coordination. The use of the proposed polydomy inspired mechanism enables the WSM to capture 16% on average of the requested ECV.
4) Scenario 4: The space segment incorporates the proposed polydomy-inspired mechanism. The WSM experiencing catastrophic failures can access sub-components of other WSMs via the MMs coordination. The use of the proposed polydomy inspired mechanism enables the WSM to capture 21% on average of the requested ECV.

The simulation results for these scenarios are shown in Figure 6-7.

From the results in Figure 6-7, it can be seen that the proposed mechanism outperforms the mechanism proposed in [85]. This is because of the formation of super-colonies that enable fracsats with non-functional CCMs to utilise the MMs. In addition, the accessible space segment data increases with the network size for all the scenarios. In the case when fracsats use the existing scheme i.e. [85], the amount of accessible ECV data is influenced by re-programming capability. In the event that multiple micro-controllers are damaged, the space segment is unable to provide users with the requested ECV. In the absence of the proposed mechanism, the micro-controller fracsat cannot network with other fracsats; since its re-programmability is lost.

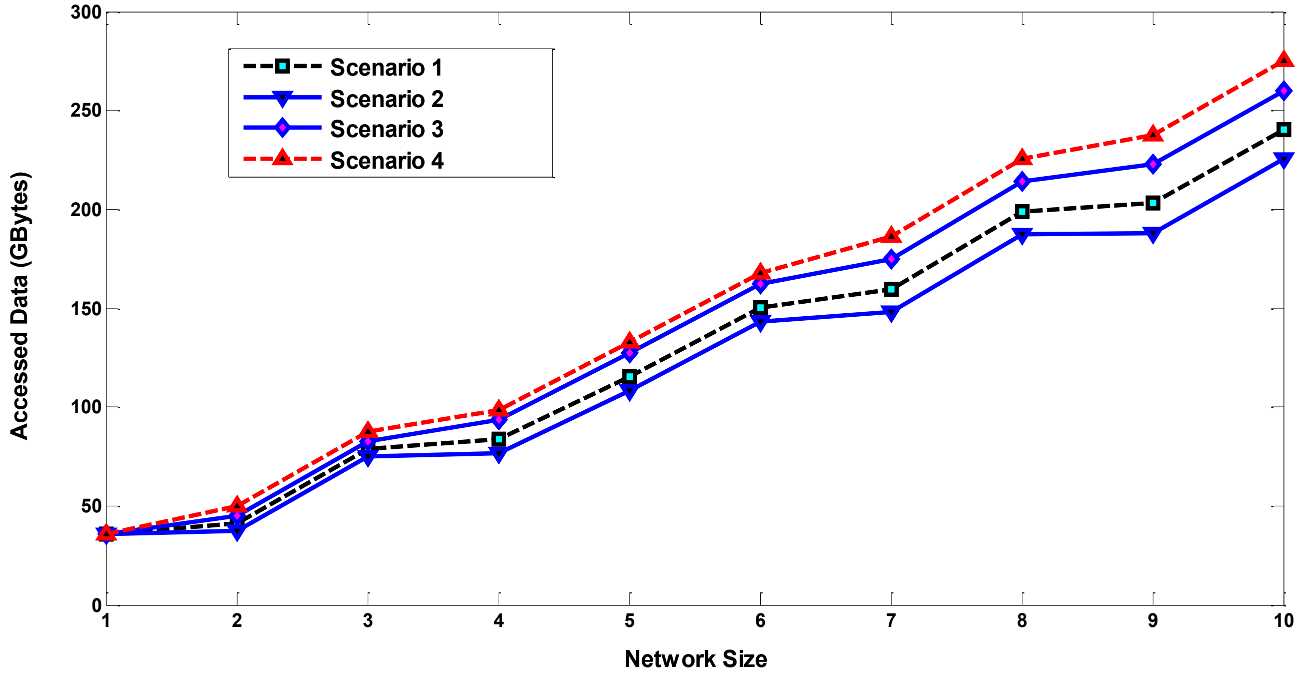

Figure 6-7: Accessible data from the space segment

Further investigations show that accessible ECV in scenario 4 exceeds that of scenario 3, by 5.4% on average. Scenario 3 outperforms scenario 1 and scenario 2 by 7.3 % and 14.2 % on average, respectively. Scenario 4 outperforms scenario 1 and 2 by 13.2% and 20.5% on average, respectively.

Chapter 7
Conclusion and Future Work

7.1 Thesis Conclusion

The research described in this thesis presents a spectrum-allocation framework that addresses the spectrum-access objectives of terrestrial radio astronomy observations, commercial earth observations and terrestrial wireless networks. Previously, the spectrum allocation for these technologies had been considered separately. The spectrum allocation framework is proposed – due to spectrum-access conflicts, technological advances and increasing spectrum demand. In addition, spectrum-access conflicts lead to interference between commercial earth observations and terrestrial wireless networks; terrestrial radio astronomy observations and intersatellite links. Furthermore, relations between terrestrial radio astronomy observations, commercial earth observations, and terrestrial wireless networks foster new synergies. These synergies can be used to design new mechanisms that improve the robustness of terrestrial radio astronomy observations, commercial earth observations, and terrestrial wireless networks.

The cognitive radio is used to reduce interference that arises between terrestrial radio astronomy observations, commercial earth observations, and terrestrial wireless networks. Cognitive radios have been identified to be suitable for solutions focused on interference reduction, enhancing spectrum utilisation, and improving user quality of service. They enable the realisation of dynamic spectrum access for future generation-spectrum allocation to emerging technologies. However, the adoption of dynamic spectruim access via cognitive radio incorporation has been largely considered for terrestrial wireless networks in comparison to terrestrial radio astronomy observations and commercial earth observation. Terrestrial radio astronomy observations experience interference increasingly from intersatellite links. In addition,the conduct of commercial earth observation has migrated from being scientific to commercial – with requirements similar to those of terrestrial wireless networks. These changes cause new spectrum access conflicts. Hence, a cognitive radio -based joint spectrum allocation model is required.

In addition,to using the cognitive radio to reduce interference, cognitive radio incorporation also ensures the sustainability of spectrum allocation. The concern of ensuring sustainable spectrum allocation has not arisen in the consideration of dynamic spectrum access for terrestrial wireless networks. Addressing the sustainability of spectrum allocation requires a joint consideration of the spectrum-access demands. In addition,to addressing sustainability, the thesis presents algorithms that aim to enhance the performance of terrestrial radio astronomy observations, commercial earth observations, and terrestrial wireless networks.

The thesis provides a literature review that examines the advances for terrestrial radio astronomy observations, commercial earth observations, and terrestrial wireless networks. In addition, it develops interference reduction mechanisms for terrestrial radio astronomy observations and commercial earth observations. Furthermore, mechanisms that improve user performance are also developed.

It develops intelligent mechanisms that enhance user performance in terrestrial wireless networks. The developed mechanisms considers similarities between training parameters in homogeneous terrestrial wireless networks and heterogeneous wireless networks. Furthermore, mechanisms that incorporate meta-cognition in cognitive radios have also been developed and shown to enhance terrestrial wireless network user performance.

Commercial earth observation networks incorporate mobile-ground stations and should be capable of supporting interactive and ubiquitous access to earth-climate variables. Mobile subscribers should be able to interact with commercial earth observation. A commercial earth observation network model, called the cognitive earth observation network , is also presented. The cognitive earth observation network differs from existing models by incorporating cognitive radio-equipped mobile ground stations and a bio-inspired low earth orbit fractionated satellite network. It supports user interaction-based demand for data. The cognitive earth observation network 's space segment is designed using ant polydomy mechanisms to enable module sharing, and to reduce the operational overhead.

The study also points out that terrestrial radio astronomy observations experience interference from intersatellite links. The thesis proposes the incorporation of generative-artificial intelligence in terrestrial wireless network - base stations. The terrestrial wireless network base stations interact with the high performance computing infrastructure and use the high performance computing infrastructure for developing terrestrial wireless network learning algorithms. The interaction enhances terrestrial radio astronomy observation power efficiency. In addition, the thesis also proposes the use of multi-mode earth-stations. The use of multimode earth stations improves terrestrial radio astronomy observation angular resolution and reduces costs of conducting terrestrial radio astronomy observations.

The thesis demonstrates that intelligent mechanisms can be used to enhance terrestrial wireless networks, terrestrial radio astronomy observations and commercial earth observation. It is also shown that the use of cognitive radio spectrum-prediction mechanisms mitigates against spectrum access conflicts and ensures sustainable spectrum allocation. These goals are achieved, while enhancing spectrum utilisation.

The contributions of this thesis aim to reduce interference among users of terrestrial wireless networks, commercial earth observations and terrestrial radio astronomy observations that require access to significant bandwidth resources. The mechanism presented to achieve this objective also improves the performance of the concerned users. The use of the cognitive radio paradigm is considered the most appropriate approach to achieve these objectives. This is because the cognitive radio has been widely considered as a technology for realising spectrum sharing. However, the cognitive radio has been largely considered for terrestrial wireless networks. The contributions in this thesis demonstrates that the cognitive radio can be used to design mechanisms that improve user performance in terrestrial radio astronomy observations, commercial earth observation and terrestrial wireless network.

The use of the cognitive radio to reduce interference and improve user performance in terrestrial wireless networks, commercial earth observations and terrestrial radio astronomy observations is novel. The novelty in this regard is the use of the cognitive radio in a scenario comprising multiple emerging technologies and not just terrestrial wireless networks as is the current state in research.

In conclusion, the mechanisms proposed in this thesis require access to computational resources for the efficient manipulation of big data in training neural networks. The mechanisms can be implemented on a neuromorphic computing architecture. This is because the neuromorphic computing architecture is capable of efficiently executing big data computations compared to the existing Von Neumann computing architecture.

7.2 Future Research Direction

The following outstanding issues provide fertile areas for future research:

1. **Derivation of statistical model:** It is also important to derive a statistical model with a better modelling of user quality of service and terrestrial wireless network spectrum usage data and using empirical data for terrestrial wireless networks using licensed spectrum. In addition, it is important to further study and re-design and high performance computing infrastructure utilisation because of observation-limiting conditions. This will help to make further adjustments that would improve the capability of the newly modified Weibull-distribution model used in the analysis.
2. **Neural-network implementation:** Further work is required to design and integrate artificial neural networks in hardware. The artificfial neural networks are those suitable for mechanisms proposed for terrestrial wireless networks, commercial earth observations; and the generative artificial-intelligence algorithm used for high performance computing infrastructure sharing.
3. **Impact on radio astronomy:** Further research that evaluates the knowledge discovery when astronomical sources are observed, in the absence of interfering inter-satellite links, is required.
4. **Implementation complexity and computation time:** The thesis does not focus on analysing computational complexity but designing mechanisms that use cognitive radio to reduce interference and improve user performance. The mechanisms proposed in this thesis require ability and availability of a computing architecture that can efficiently process big data. This is important especially for neural network training and associated computations. The current Von Neumann computing architecture has been recognised to be incapable of efficiently executing big data operations. However, the neuromorphic computing architecture has been recognised to be suitable in this regard. The implementation of the proposed mechanisms on a neuromorphic computing architecture is a subject of future work.

References

[1] J.H.Vinson 'Communication(s) and Technology in Spectrum Implementation with Body Earth', IEEE Conference on Sustainability (SusTech), Portland, Oregon, 1-2, Aug 2013, pp 212-217.

[2] Y.Furuya, J.Takada, N.Nakajima, T.Fujii, and Y.Takeda, 'Radio Spectrum Vision in 50 Years from Now: Consideration on long term spectrum reframing mainly below 3GHz.' IEEE Conference on Standards for Communications and Networking, Tokyo, 28-30 Oct 2015, pp 7-12.

[3] S.Haykin and P.Setoodeh, 'Cognitive Radio Networks: The Spectrum Supply Chain Paradigm', IEEE Transactions on Cognitive Communications and Networking, Vol 1 No 1, March 2015, pp 3- 28.

[4] N.Panwar, S.Sharma and A.K.Singh, 'A survey on 5G: The next generation of mobile communication', Physical Communications, Vol 18 (2016), pp 64-84.

[5] M.Trusculescu, M.Balan, C.Dragasanu, A.Pandele and M.I.Piso, Nanosatellites: The Tool for Earth Observation and near Earth Environment Monitoring', (Ed) R.Rustamov, 2012, pp 25-41.

[6] T.Pultarova 'Telecommunications- Space Tycoons go head to head over mega satellite network' Engineering and Technology, Vol 10 No 2 2015, pp 20.

[7] J.R.Stuart 'Teledesic network and space infrastructure architecture and design features' IEEE International Conference on Engineering of Complex Computer Systems, Montreal, Quebec, 21-25 Oct 1996, pp 147-150.

[8] B.Lal, E.J.Sylak-Glassman and N.Gupta, 'Science & Technology Policy Institute: Global Trends in Civil and Commercial Space (Presentation)' pp 1-142, [Online] Available: https://www.ida.org/idamedia/Corporate/Files/Publications/STPIPubs/2015/d5682final.ashx Accessed: 25/05/2016.

[9] M.De Pasquade and J. Bradford 'Space Works: Nano/Micro Satellite Market Assessment, Revision C, Feb 2013, pp 1-17.

[10] K.Kelley 'Launch Systems to support the booming nanosatellite industry' IEEE Aerospace Conference, Big Sky MT, 7-14 March 2015, pp 1-6.

[11] F.E.Tubbal, R.Raad, K.W.Chin and B.Butters 'S-Band Shorted Antenna for Inter Pico-Satellite Communications' International Conference on Telecommunications Systems, Services and Applications, Kuta, 23-24 Oct 2014, pp 1-4.

[12] T.E.Gergely 'The SKA, RFI and ITU Regulations' , Workshop on Mitigation of Radio Frequency Interference in Radio Astronomy, July 16-18,2004, Penticton, Canada, pp 1-10.

[13] M.J.Bentum, A.J.Boonstra and W.A.Baan, 'Impact of Cognitive Radio on Radio Astronomy ', RFI Mitigation Workshop, Groningen, 29-31, March 2010, pp 1-7.

[14]D.Barbosa, M.Bergano, V.A.R.M.Ribeiro, A.Loots, V.L.Thondikulam, M.Gaylard, A.V.Ardene, C.Paulo, S.ColaFrancesco, J.C.Amador, R.Maia and R.Melo 'Design, environmental and sustainability constraints of new African Observatory: The example of the Mozambique Radio Astronomy Observatory', IEEE Africon, Pointe-Aux-Piments, 9-12 Sept 2013, pp 1-5.

[15] D.Barbosa, A.J.Boonstra, R.Aguiar, A.V.Ardene, De.S.Vela and L.V.Montnegro 'A sustainable approach to large ICT Science based infrastructure: The case for radio astronomy', IEEE International Energy Conference (ENERGYCON), 13-16, May 2014,Cavtat, pp 668-674.

[16]M.Wellens and P.Mahonen, 'Lessons Learned from an extensive spectrum occupancy measurement campaign and a stochastic duty cycle model' Mobile Network and Applications, Vol 15, 2010, pp 461-474.

[17] A.Martian, C.Vladeanu, D.Fratu, I.Marghescu and S.E.Assad, 'Spectral Occupancy Measurement in Rural and Urban Environments: Analysis and Comparison' Advanced International Conference on Telecommunications, June 23-28, 2013, Rome, Italy, pp 78-83.

[18]S.Haykin 'Cognitive Radio : Brain Empowered Wireless Communications', IEEE Journal on Selected Areas in Communications, Vol 23, No 2, Feb 2005, pp 201-220.

[19] A.B.Mackenzie, J.H.Reed, P.Athanas, C.W.Bostian, M.R.Buerhrer, L.A.DaSilva, S.W.Ellingson, Y.T.Hou, M. Hsiao, J.Park, C.Patterson, S.Raman and C.da.Silva 'Cognitive Radio and Networking Research at Virginia Tech' Proceedings of the IEEE, Vol 93 No 4, 07 April 2009, pp 660-687.

[20] T.Yucek and H.Arslan 'A Survey of Spectrum Sensing Algorithms for cognitive radio applications', IEEE Communications Surveys & Tutorials, 04 March 2009, pp 116-130.

[21] J.Mitola III and G.Q.Maguire Jnr 'Cognitive Radio: Making Software Radios More Personal' IEEE Personal Communications, Vol 6 No 4, August 6, 2002, pp 13-18.
[22] S.Bai, X.Zhou and F.Xu 'Soft decision spectrum prediction based on back propagation neural networks' International Conference on Computing, Management and Telecommunications, 27-29 April 2014, Da Nang, pp 128-133.
[23] X.Xing, T.Jing, W.Cheng, Y.Huo and X.Cheng 'Spectrum Prediction in Cognitive Radio Networks', IEEE Wireless Communications, Vol 20 No 2, 25 April 2013, pp 90-96.
[24] D.Darmon, J.Sylvester, M.Girvan and W.Rand, 'Predictability of user behaviour in Social Media: Bottom-Up v. Top-Down Modelling ', International Conference on Social Computing, 8-14 Sept 2014, Alexandria VA, pp 100-103.
[25] A.He, K.K.Bae, T.R.Newman, J.Gaeddert, K.Kim, R.Menon, L.M.Tirado, J.J.Neel, Z.Youping, J.H.Reed and W.H.Tranter 'A Survey of Artificial Intelligence for Cognitive Radios' IEEE Transactions on Vehicular Technology' Vol 59 No 4, 27 May 2010, pp 1577-1590.
[26]M.Bkassiny, Y.Li and S.K.Jayaweera 'A Survey on Machine Learning Techniques in Cognitive Radios' IEEE Communications, Surveys & Tutorials, Vol 15 No 3, 31 July 2013, pp 1096-1129.
[27] N.Abbas, Y.Nassar and K.E.Ahmed 'Recent Advances on artificial intelligence and learning techniques in cognitive radio networks' , Eurasip Journal on Wireless Communications and Networking , 2015, 174, pp 1-20.
[28] B.G.Najashi and W.Feng, 'Cooperative Spectrum Occupancy Based Spectrum Prediction Modelling, Journal of Computational Information Systems, 10:10, 2014, pp 4091-496.
[29] C.Xu, Y.Li, Y.Yang and Y.Xian, 'A Novel Spectrum Prediction Algorithm for Cognitive Radio System Based on Chaotic Neural Network, 'Journal of Computational Information Systems, Vol 9 No 1, 2013, pp 313-320.
[30] H.Li, X.Wu, B.Wu and X.Chen, 'Multilayer Feedforward Neural Network Based Efficient Spectrum Occupancy Prediction Scheme for Cognitive Radio System', Journal of Computational Information Systems, Vol 10, No 10, 2014, pp 4017-4028.
[31] E.Tsakalaki, O.N.Alrabadi and A.Tatomirescu, De.E.Carvello and G.E.Petersen, 'Concurrent Communication and Sensing in Cognitive Radio Devices: Challenges and an Enabling Solution', IEEE Transactions on Antennas and Propagations, Vol 62 No 3, Mar 2014, pp 1090-1097.
[32] S.Koba , K.Tsukamoto, M.Tsuru and Y.Oie , 'Cognitive Radio Aware Transport Protocol for Mobile Ad-Hoc Networks' International Conference on the design of Reliable Communication Networks, 4-7 March 2013, Budapest, pp 131-138.
[33] E.F.CharlesLaBerge, 'System Design Considerations for the Development of the Iridium World Air Services' Proceedings, Digital Avionics Systems Conference, St. Louis, MO, 24 Oct 1999-29 Oct 1999, pp 6.C.3-1 – 6.C.3-8.
[34] I.Kucuk 'Radio Astronomy in Turkey: Site Selection Studies for Radio Quiet Zones' RFI Mitigation Workshop, 29-31 March 2010, Groningen, Netherlands, pp 1-6.
[35] T.Hidayat 'Developing Radio Astronomy at Bosscha Observatory' International Conference on Instrumentation, Communications, Information Technology and Biomedical Engineering, Bandung, 7-8 November 2013, pp 10-15.
[36] R.Umar, Z.Z.Abidin, Z.A.Ibrahim, Z.Rosh and N.Noorazlen 'Selection of Radio Astronomical Observatory Sites and its dependence on human generated RFI', Research in Astronomy and Astrophysics, Vol 14 No 2, pp 241-248.
[37] R.Umar, Z.Z.Abidin, Z.A.Ibrahim 'The Importance of Site Selection for Radio Astronomy' Journal of Physics: 539 (2014), pp 1-8.
[38] N.H.Sabri, R.Umar, W.Z.A.W.Mokhtar, Z.Z.Abidin, Z.A.Ibrahim, A.Azid, H.Juahir, M.E.Toriman, M.K.A.Kamarudin 'Preliminary Study of Vehicular Effect on Radio Signal for Radio' Jurnal Teknologi Vol 75 No 1, 2015, pp 313-318.
[39] C.R.Boshuizen, J.Mason, P.Kluper and S.Spanhake 'Results from the PlanetLabs Flock Constellation', AIAA/USU Conference on Small Satellites, Logan, 7 August 2014, pp 1-8.
[40] M.R.Maheshwarrappa and C.P.Bridges ' Software Defined Radios for small satellites' NASA/ESA Conference on Adaptive Hardware and Systems, Leicester, 14-17 July 2014, pp 172-178.

[41] M.R.Maheshwarrappa, M.Bowyer and C.P.Bridges ‘Software Defined Radio (SDR) Architecture to support multi-satellite communications’ IEEE Aerospace Conference Big Sky MT, 7-14 March 2015, pp 1-10.
[42] N.Faber, Y.Nakamura, R.Alera, D.Mauro, C.R.Frost, G.Btat and J.McNair, ‘Heterogeneous Spacecraft Network: General Concept and Case Study of a cost effective multi-institutional earth observation platform’ IEEE Aerospace Conference, 1-8 March 2014, Big Sky MT, PP 1-16.
[43] W.Edmonson, S.Gebrayohannesand, A.Dillion , R.Radhakrishnan, J.Chenou, A.Esterline and F.Afghah , ‘Systems Engineering of Intersatellite Communications for Distributed Systems of small Satellites’ IEEE International Systems Conference,13-16 April 2015, Vancouver, pp 705-710.
[44] S.E.Palo ‘High Rate Communications Systems for CubeSats’ International Microwave Symposium, Phoenix, 17-22 May 2015, pp 1-4.
[45] R.N.Simms and K.Goverdhanam ‘Applications of Nano Satellites and Cube-Satellites in Microwave and RF Domain’ International Microwave Symposium, Phoenix, 17-22 May 2015, pp 1-4.
[46] A.Mauthe and E.Monteiro, ‘Outrageous Opinion Panel: Do we really have to consider the human factor in networking? Future Human Centric Multimedia Networking, August 16, 2013, Hong Kong, pp 59.
[47] A.Anderson and H.Haas , ‘Using Echo State Network to Characterize Wireless Channels’, IEEE Vehicular Technology Conference, Dresden, 2-5 June 2013, pp 1-5.
[48] A.Shahid, S.Aslam, H.S.Kim and K.G.Lee, ‘CSIT: Channel State and Idle Time Prediction using a neural network for Cognitive LTE-Advanced Network’, Eurasip Journal on Wireless Communications and Networking, 2013:203, pp 1-16.
[49] O.Winston, A.Thomas and W.OkelloOdongo ‘Optimizing Neural Network for TV Idle Channel Prediction in Cognitive Radio
Using Particle Swarm Optimization’, International Conference on Computational Intelligence, Communication Systems and
Networks, Madrid, 5-7 June 2013, pp 25-29.
[50] K.Tsakgaris, A.Bantouna and P.Demestichas , ‘Self-Organizing Map for Advanced Learning in Cognitive Radio Systems’, Computers and Electrical Engineering , Vo 38 No 4, July 2012, pp 852-870.
[51] B.Shaswar, H.Oliver and A.Aghvami , ‘Wireless Standard Classification in Cognitive Radio Networks using Self organizing maps’ , International Symposium on Wireless Communication Systems, Ilmenau, 27-30 Aug 2013, pp 1-5.
[52] M.Bauduin, A.Smerieri, S.Masser and F.Horlin, ‘Equalization of the Nonlinear satellite Communication Channel with an Echo state network’, IEEE Vehicular Technology Conference, Glasgow, 11-14 May 2015, pp 1-5.
[53] G.V.Lakhekar and R.G.Roy, ‘A Fuzzy Neural Approach for dynamic spectrum allocation in cognitive radio networks’ International Conference on Circuit, Power and Computing Technologies, Nagercoil, 20-21 March 2014, pp 1455-1461.
[54] V.Rakovic and L.Gavrilovska ‘Novel RAT selection Mechanism based on Hopfield Neural Networks’ International Congress on Ultra-Modern Telecommunications and Control Systems and Workshops, Moscow, 18-20 Oct 2010, pp 212-217.
[55] K.R.Rao, Z.S.Bojkovic and B.M.Bakmazi, ‘Network Selection in Heterogeneous Environment: A step towards always best connected and served.’ International Conference on Telecommunication in Modern Satellite, Cable and Broadcasting Services, Nis, 16-19 Oct 2013, pp 82-90.
[56] D.Koutsomanis ‘Artificial Intelligence for Ethology: Neural Networks in the prediction of human behavior’, International Conference on Computer Modelling and Simulation, Cambridge, 26-28 Mar 2014, pp 32-35.
[57] J.Constantine, Y.Tawk, S.E.Barbin and C.G.Christodoulou ‘Reconfigurable Antennas: Design and Applications’, Proceedings of the IEEE, Vol 99 No 3 March 2015, pp 424-437.
[58] J.C.Lyke, C.G.Christodoulou, G.A.Vera, and A.H.Edwards, ‘An Introduction to Reconfigurable Systems’, Proceedings of the IEEE, Vol 3 No 3, pp 289-317, March 2015.
[59] O.E.Falowo and H.A.Chan , ‘RAT selection for Multiple Calls in Heterogeneous Wireless Networks using Modified TOPSIS Group Decision Making Technique’ International Symposium on Personal Indoor and Mobile Radio Communications, Toronto, 11-14 Sept 2011, pp 1371-1375.

[60] N.Abbas, S.Taleb, H.Hajj and Z.Dawy, 'A Learning Based Approach for Network Selection in WLAN/3G Heterogeneous Network' International Conference on Communications and Information Technology, Beirut, 19-21 June 2013, pp 309-313.
[61] X.Chen, H.Wang, H.Lv, A.Ali and Z.Wang, 'Application of fuzzy comprehensive evaluation in cognitive networks for optimal network selection', Applied Mathematics and Information Sciences, Vol 8 No 1 2014, pp 415-422.
[62] K.L.Haldar. C.Ghosh, and D.P.Aggrawal, 'Dynamic spectrum access and network selection in heterogeneous cognitive wireless networks' Pervasive and Mobile Computing, Vol 9 2013, pp 483-493.
[63] P.B.Selding, 'ESA Combats Ground Interference to Earth Observation Satellites [Online] Available: spacenews.com', Accessed June 13, 2014.
[64] C.Patton 'WRC-15: Winning the Spectrum war' [Online] Available: www.satellitetoday.com.
[65] K.Liolis, G.Schlueter, J.Krause, F.Zimmer, L.Combelles, J.Grotz, S.Chatzinotas, B.Evans, A.Guidotti, D.Tarchi and A.V.Coralli, 'Cognitive Radio Scenarios for Satellite Communications: The CoRaSat approach'Future Network and Mobile Summit, 3-5 July 2013, Lisboa, pp 1-10.
[66] M.Tercero, K.W.Sung and J.Zander 'Exploiting Temporal Secondary Access Opportunities in Radar Spectrum' Wireless Personal Communications, 2013, Vol 72, pp 1663-1674.
[67] H.Deng and B.Himed 'Interference reductionProcessing for Spectrum Sharing between Radar and Wireless Communication Systems' IEEE Transactions on Aerospace and Electronic Systems , Vol 49 No 3, July 2013, pp 1890-1898.
[68] S.Heuel and A.Roessler 'CEOxistence of S-band Radar and 4G Mobile Networks' International Radio Symposium,16-18 June 2014,Gdansk, pp 1-4.
[69] V. Pankonin and R.M.Price 'Radio Astronomy and Spectrum Management: The Impact of WARC-78' IEEE Transactions on Communications, Vol .Com 29, No 8, 1981, pp 1228-1237.
[70] P.J.Waterman 'Conducting Radio Astronomy in the EMC Environment', IEEE Transactions on Electromagnetic Compatibility, Vol EMC-26, No 1, February 1984, pp 29-33.
[71] J. Isnard 'Frequency Band Sharing: Utopia or Reality' IEEE AESS Systems Magazine, May 2002, pp 4-9.
[72] D.R.DeBoer, S.L.C.Pol, M.M.Davis, T.Gaier, P.Feldman, K.I.Kellerman, D.G.Long, L.Magnani, D.S.McKague, T.J.Pearson, A.E.E.Rogers, S.C.Reising, G.Taylor, A.R.Thompson and L.V.Zee 'Radio Frequencies: Policy and Management', IEEE Transactions on Geoscience and Remote Sensing, Vol 51, No 10, Oct 2013, pp 4897-4907.
[73] M.Hoare and S.Rawlings, 'Recycling for radio astronomy' Astronomy and Geophysics Vol 53 No 1, 2012, pp 1.19-1.21.
[74] B.D.Asabere, M.J.Gaylard, C.Horellou, H.Winkler and T.Jarrett, 'Radio Astronomy in Africa: the case of Ghana', April 2015, pp 1-6, [Online] Available http://arxiv.org/pdf/1503.08850.pdf
[75] L.Woodburn, T.Natuschm S.Weston, P.Thomasson, M.Godwin , C.Granet and S. Gulyaev, 'Conversion of a New Zealand 30 meter Telecommunications Antenna into a Radio Telescope , Astronomical Society of Australia, 2015, doi: 10.1017/pas.2015.xxx. [Online] Available http://arxiv.org/pdf/1407.3346.pdf pp 1-1.
[76] H-R.Klockner, S.Rawlings, I.Heywood, R.Beswick, T.W.B.Muxlow, S.T.GarrinGBTon, J.Hatchell, M.G.Hoare, M.J.Jarvis, I. Jones, H.J.VanLangevelde, 'Goonhilly: a new site for e-Merlin and the EVN' European VLBI Network Symposium and EVN Users Meeting: VLBI and the new generation of radio arrays', Sep 20-24, 2010, Manchester [Online] Available: http://www.jive.nl/~huib/Archive/11033600v1_goonhilly.pdf, pp 1-10.
[77] P.Behnke, D.Soberol, S.Bredawag, B.Dunne, A.Sterian and D.Furton 'Senior Capstone: A Software Defined Radio Design for Amateur Astronomy' Interdisciplinary Engineering Design Education Conference, 4-5 March 2013, Santa Clara, pp 100-108.
[78] J.Katmanzi and M.Kahn 'Development of Renewable Energy Based Cooling System for a mobile ground station' IEEE Aerospace and Electronic Systems Magazine, Vol 30 No 2, 18 Mar 2015, pp 6-13.
[79] C.Fish, S.Slagowski, L.Dyrud, J.Fentzke, B.Hargis and M.Steerman 'Pull vs Push: How Omni Earth Delivers Better Earth Observation Information to Subscribers' The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-7/W3, International Symposium on Remote Sensing of Environment, 11-15 May 2015, Berlin, Germany, pp 1083-1087.

[80] G.Zhou ‘Future Intelligent Earth Observation Satellite System (FIEOS): Advanced System of Systems, (Ed) A.V.Gheorghe, 2012, pp 95-103.
[81] R.C.Santiago, M.Szydelko, A.Kliks, F.Foukalas, Y.Haddad, K.E.Nolan, M.Y.Kelly, M.T.Masonta and I.Balasingham, ‘5G: The Convergence of Wireless Communications’ Wireless Personal Communications, Vol 83, 2015, pp 1617-1642.
[82] C.Hei, K.Niu , Z.He , J.Lin and S.Sun ‘A design scheme of Cognitive LTE-A radio networks’ International Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications, 29-31 Oct 2013, Chengdu, pp 65-70.
[83] J.D.Deaton, R.E.Irwin and L.A.daSilva, ‘Dynamic Spectrum Access in LTE-Advanced’, Elsevier Journal of Physical Communications,Vol 10 Mar 2014, pp 127-143.
[84] V.Osa, C.Herranz, J.F.Monserrat and X.Gelabert, ‘Implementing Opportunistic Spectrum Access in LTE-Advanced’, Eurasip Journal on Wireless Communications and Networking, 2012:95, pp 1-17.
[85]A.O.Erlank and C.P.Bridges ‘A Multicellular Architecture towards low cost satellite reliability’ NASA/ESA Conference on Adaptive Hardware and Systems (AHS), 15-18 June 2015, Montreal, pp 1-8.
[86] P.S.Kim, D.Levy and P.P.Lee ‘MODELLING AND SIMULATION OF THE IMMUNE SYSTEM AS A SELF REGULATING NETWORK’ Models in Enzymology Volume 467 Elsevier, 2009 pp 78-103.
[87] J.Quintin, S.C.Cheng, J.W.M van der Meer and M.G Netea‘Innate immune memory: towards a better understanding of host defense mechanism’ ScienceDirect Current Opinion in Immunology 2014:29 pp 1-7
[88] C.D.Balaban, S.W.Ogburn, S.G.Warshafsky, A.Ahmed and B.J.Yates ‘Identification of Neural Networks that contribute to motion sickness through principal component analysis of FoS Labelling Induced by Galvanic Vestibular Stimulation’, PLOS One, Vol 9 No 1, 2014, pp 1-14.
[89] H.Demuth and M.Beale ‘Neural Network Toolbox’ Math works User’s Guide Version 4.
[90] H.Asadi, H.Volos, M.M.Marefat and T.Bose, ‘Metacognitive Radio Engine Design and Standardization’ IEEE Journal on Selected Areas in Communications, Vol 33, No 4, April 2015, pp 711-724.
[91] H.Asadi, H.Volos, M.M.Marefat and T.Bose, ‘Meta-cognition and the next generation of cognition engines’ IEEE Communications Magazine, Vol 54, No 1, January 2016, pp 76-82.
[92] G.Tononi and C.Koch, ‘Consciousness: here, there and everywhere’ Philosophical Transactions B of the Royal Society,30 March 2015,pp 1-18.
[93] J.R.Ryan and M.Chiodin, ‘Where is my mind? How Sponges and Placozoans may have lost neural cell types’, Philosophical Transactions B of the Royal Society, 12 August 2015, pp 1-6.
[94] K.M.Stiefel, A.Merrifield and A.O.Holcombe ‘The claustrum’s proposed role in consciousness is supported by the effect and target localization of Salvia divinorum’ frontiers in Integrative Neuroscience, February 2014, Vol 8 No 20, pp 1-7.
[95] Y.Goll, G.Atlan and A.Citri, ‘Attention: the claustrum’ Trends in Neurosciences, Vol 38 No 8, August 2015, pp 486-495.
[96] A.Budianu, A.Meijerink and M.J.Bentum ‘Swarm to Earth Communication in OLFAR’, Acta Astronautica, Vol 103, 2015, pp 14-19.
[97] J.M.Ford and K.D.Buch ‘RFI Mitigation Techniques in Radio Astronomy’ IEEE International Geoscience and Remote Sensing Symposium, Quebec City, 13-18 July 2014, pp 231-234.
[98] M.J.Marcus ‘Where Does the Radio Spectrum End’, IEEE Wireless Communications, Vol 20 No 3, 2013, pp 6-7.
[99] T.V.D.Zant, M.Kouw, and L.Schomaker, ‘Generative Artificial Intelligence’ in Philosophy and Theory of Artificial Intelligence , (Ed), V.C.Muller, Vol 5, 2012, pp 103-120.
[100] K.P.Bagadi and S.Das, ‘Multiuser Detection in SDMA-OFDM Wireless Communications using Complex Multilayer Perceptron Neural Network’ Wireless Personal Communications, Vol 77, 2014, pp 21-39.
[101] P.Andreani, ‘ALMA Cycle 3 Proposer’s Guide and Capabilities’, Doc 3.2, Ver 1.0, March 2015, pp 1-46.
[102] S.J.Almalki and J.Yuan, ‘A new modified Weibull distribution’, Reliability Engineering & System Safety, Vol 111, March 2013, pp 164-170.
[103] A.J. Kemball and T.J. Cornwell A Simple Model of Software Costs for the Square Kilometer Array, Experimental Astronomy, Vol 17, 2004, pp 317-327.

[104]B.LeMay, ‘Agilent Technologies Introduced Basic Spectrum Analyzer for Budget Driven Applications’ [Online] http://www.agilent.com/about/newsroom/presrel/2012/30nov-em12148.html
[105]WORLD METEOROLOGICAL ORGANIZATION, ET-SAT-6/Doc.64 (3.III.2011), [Online] Available: http://www.wmo.int/pages/prog/sat/meetings/documents/ET-SAT-6_Doc_06-04_ECVGapAnalysis.pdf
[106] M.D.Mura, F. Pacifici, P.Gamba, J.Chanussot and J.A.Benediktsson ‘Challenges and Opportunities of Multimodality and Data fusion in Remote Sensing’ Proceedings of the IEEE, Vol 102 No 8, 13 Aug 2015, pp 1584-1601.
[107] R.Boudjemaa ‘Optimal Placement of Weather Radar Network in Complex terrain using swarm intelligence’ European Conference on radar in meteorology and hydrology, 1-5 Sept 2014, Germany, Abstract ID 168, pp 1-7.
[108] M.Poblet ‘Affordable Telecommunications: A new digital economy is calling’ Australian Journal of Telecommunications and the Digital Economy, Vol 1 No 1 Article 12, Nov 2013.
[109] E.Baceski, S.Gokcebog, A.Erdem, S.G.Erboy, M.Akyol, K.Arslankoz, I.Arslan, M.A.Agca, Y.B.Aydin, A.R.Arslan and O.Ceylan ‘HAVELSAT: A Software Defined Radio Experimentation CubeSat’ International Conferences on Recent Advances in Space Technologies, Istanbul, 16-19 June 2015, pp 821-824.
[110] L.Wei, Q.Zhang, X.Xiangjun and Y.Yongjun ‘A real time data transmission fractionated satellite system based on data relay satellite system’ International Conference on Information Science and Control Engineering, Shenzen, 7-9 Dec 2012, pp 1-5.
[111] A.Dubay, W.Emfinger, A.Gokhale, G.Karsas, W.R.Otte, J.Parsons and C.Szabo, ‘A Software Platform for fractionated spacecraft ’, IEEE Aerospace Conference, 3-10 March 2012, Big Sky MT, pp 1-20.
[112] J.Chu, J.Guo and E.K.A.Gill, ‘Fractionated Space Infrastructure for Long Term Earth Observation Missions’ IEEE Aerospace Conference, Big Sky MT, 2-9 March 2013, pp 1-9.
[113] W.Han, B.Wang, B.Zhao , J.Teo and Z.Tang ‘HANDS : A Heterogeneous Aerospace Network Architecture for Disaggregated Satellite Based on Spacewire Networks and Protocols ’ International SpaceWire Conference , 22-26 Sept 2014, Athens, pp 1-4.
[114] M.B.Boissin, A.Gleyzes and C.Tinel ‘The Pleiades System and Data Distribution’ IEEE International Conference on GCEOscience and Remote Sensing Symposium, 22-27 July 2012, Munich, pp 7098-7101.
[115]European Space Agency (ESA) Sentinel Overview [Online] Available http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Overview4. Accessed: May 23/05/ 2016.
[116] E.Gill, P.Sundaramoorthy, J.Bouwmeester, B.Zandbergen and R.Reinhard ‘Formation Flying Within a Constellation of Nano Satellites: The QB50 Mission’, Acta Astronautica, 82 (2013), pp 110-117.
[117] M.A.Zafrara, A.Boudjemai and N.Boughanmi ‘ALCUBESAT-1: First Algerian University Project for Educational Purpose’ International Conference on Recent Advances in Space Technologies, 16-19 June 2015, Istanbul, pp 796-802.
[118] M.Safyan, ‘Overview of the Planet Labs Constellation of Earth Imaging Satellites: In Space to Help Life on Earth’, March 2015, pp 1-23, [Online]Available:https://www.itu.int/en/ITU-R/space/workshops/2015-prague-small-sat/Presentations/Planet-Labs-Safyan.pdf Accessed: 24/05/2016.
[119] J.Straub ‘A Review of Spacecraft AI Control Systems’ Online, Accessed 14/09/2015.
[120] M.Hinchey, ‘Families (of Products) In Space’ International Software Product Line Conference, Munich, 22-26 Aug 2011, pp 8-9.
[121] E.Vassev and M.Hinchey ‘Self Awareness in Autonomous Nano-Technology Swarm Missions’ IEEE Conference on Self Adaptive and Self-Organizing Systems Workshops, 3-7 Oct 2011, Ann Arbor, Mil, pp 133-136.
[122] T.Kanechika, K.Oono, Y.Segawa, K.Yagi , T.Imoto, and Y.Morita, ‘Epsilon Launch Vehicle First Flight and its Evolutions’ 28TH Annual AIAA/USU Conference on Small Satellites, Logan Utah Aug 4-7,2014, Utah, pp 1-6.
[123] Z.Yuan , Y.Chen and R.He ‘Agile Earth Observing Satellites Mission Planning Using Genetic Algorithms Based on High Quality Initial Solutions ’, IEEE Congress on Evolutionary Computation ,6-11 July 2014, Beijing, pp 603-609.

[124] Z.Chen and Y.Zeng ‘A Swarm Intelligence Networking for Small Satellite Systems’Communications and Network, 2013,Vol 5,pp 171-175.
[125] C.Iacopino , P.Palmer , A.Brewer and N.Policela ‘Constellation MPS based on ant colony optimization algorithms’International Conference on Recent Advances in Space Technologies, 12-14 June 2013, Istanbul, pp 159-164.
[126] Z.Yan and Y.Chen, ‘Integration Schedule of Agile Satellite Based on Improved Ant Colony Algorithm’ International Conference on Emergency Management and Management Sciences, 1-8 Jan 2013, China, pp 1-4.
[127] E.J.H.Robinson ‘Polydomy: The Organisation and Adaptive Function of Complex nest systems in ants’Current Opinion in Insect Science, Vol 5, 2014, pp 37-43.
[128] M.Saar, L.Leniaud, S.Aron and A.Hefetz, ‘At the brink of super-coloniality: genetic, behavioural and chemical assessments of population structure of the desert ant cataglyphis niger’ 01 May 2014, Vol 2, Article 13, pp 1-10.
[129] P.Kennedy, T.Uller and H. Helantera ‘Are ant supercolonies crucibles of a new major transition in evolution’,Journal of Evolutionary Biology, Vol 27 2014, pp 1774-1785
[130] J.Straub, G.R.Williams, J.Pettis, I. Fries, and P.Neumann,‘Superorganism resilience: eusociality and susceptibility of ecosystem service providing insects to stressors. Current Opinion in Insect Science, 2015, 12, pp 109-112.
[131]T.A.O’Shea-Wheller, A.B.Sendova-Franks and N.R.Franks,‘Differentiated Anti Predation Responses in a superorganism’PLOS ONE 10 (11) Nov 11, 2015, pp 1-10.
[132] J.Z.Shik, C.Hou, A.Kay, M.Kaspari and J.F.Gilloly,‘towards a general life-history of the superorganism:predicting the survival, growth and reproduction of ant societies’ Biology Letters, Vol 8 15 August 2012, pp 1059-1062.

Appendix

The simulation of the proposed mechanisms have been conducted in MATLAB. The MATLAB commands ***tic*** and ***toc*** have been used to determine the duration of algorithm execution.

The neural network used in the heterogenenous mode of the proposed dual mode mechanism is designed using the MATLAB neural network object oriented package. The package allows the setting of more parameter values than permitted in the graphic user interface tool. The neural network has been trained using data modelled from real life network performance measurement distribution.

In the case of the mechanisms, learning classification pause and learning diversity selection, the wireless channel is modelled after the LTE channel model as defined in the third generation partnership standards. The channel modelling involved the choice of radio signal angle of arrival, mean distance between antennas in the mobile subscriber and the LTE-Advanced evolved Node B. The simulation procedure involved the use of parameters such as user orientation to the LTE-Advanced evolved Node B. The channel model is used to compute the channel co-efficients. The transmit power of the cognitive radio is assumed to be higher than the power radiated by interferers on a neighbouring channel. In addition, the additive white gaussian noise is not assumed to exceed interference power.

The scale of transmit power used by the cognitive radio is in the order of milliWatts while the scale of transmit of power used by interferers to the cognitive radio is in the scale of tenths of milliWatts. In addition, it is assumed that the cognitive radio in the LTE-Advanced does not spend any period exceeding the measurement gap length in acquiring training data.

The packet loss rate has been examined with the assumption that the use of the neural network in executing spectrum prediction has an high accuracy in predicting the expected output parameters. This is obtainable when the artificial neural network has been well trained. It is also assumed that the interference occurs due to the wrong prediction of expected output parameters. In addition, it is also assumed that the artificial neural network prediction accuracy is differs for wireless network channels.

In simulating the performance of the mechansism proposed for improving terrestrial radio astronomy, the newly modified Weibull distribution is used to describe relations between the number of telescopes and computing resources. The newly modified Weibull distribution is simulated using distribution parameters that yield a positive probability value. In the integration of the newly modified Weibull distribution, terms up to the third order alone have been considered in the numerical simulation. This is because higher order terms are observed to be significantly small.

It is assumed that user earth observation requirements necessitate a joint observation by sensors on functional satellites. In addition, the training data for the neural network used by the mobile ground station is simulated using the Pareto distribution. In examining the amount of accessed data, it is assumed that data is stored on the ground based meteorological station.